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PHYSIOLOGY OF FLIGHT

HUMAN FACTORS IN THE OPERATION OF MILITARY AIRCRAFT

This manual replaces manual of the same title published in 1942 by Aero Medical Laboratory, Engineering Division, Air Technical Service Command, Wright Field, Dayton, Ohio.

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Foreword

Headquarters Army Air Forces,
Washington 25, D.C.
25 February 1945

The advances in aircraft performance in speed, altitude, and duration of flight in the past three years have made more important than ever before a clear understanding of man's physiological limitation. This manual presents the present state of knowledge of some of the more important physiological problems in aviation.

Initial distribution of this manual will be made to each medical officer, aviation physiologist, and personal equipment officer in the Army Air Forces.

Additional copies to complete the above distribution, and for others in the Army Air Forces who may desire copies may be obtained by request from Commanding General, Fairfield Air Technical Service Command, Patterson Field, Fairfield, Ohio. Attn: Publication Distribution Branch.

BARNEY M. GILES,
Lieutenant General, United States Army,
Deputy Commander Army Air Forces and
Chief of Air Staff.

HEADQUARTERS ARMY AIR FORCES
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Introduction

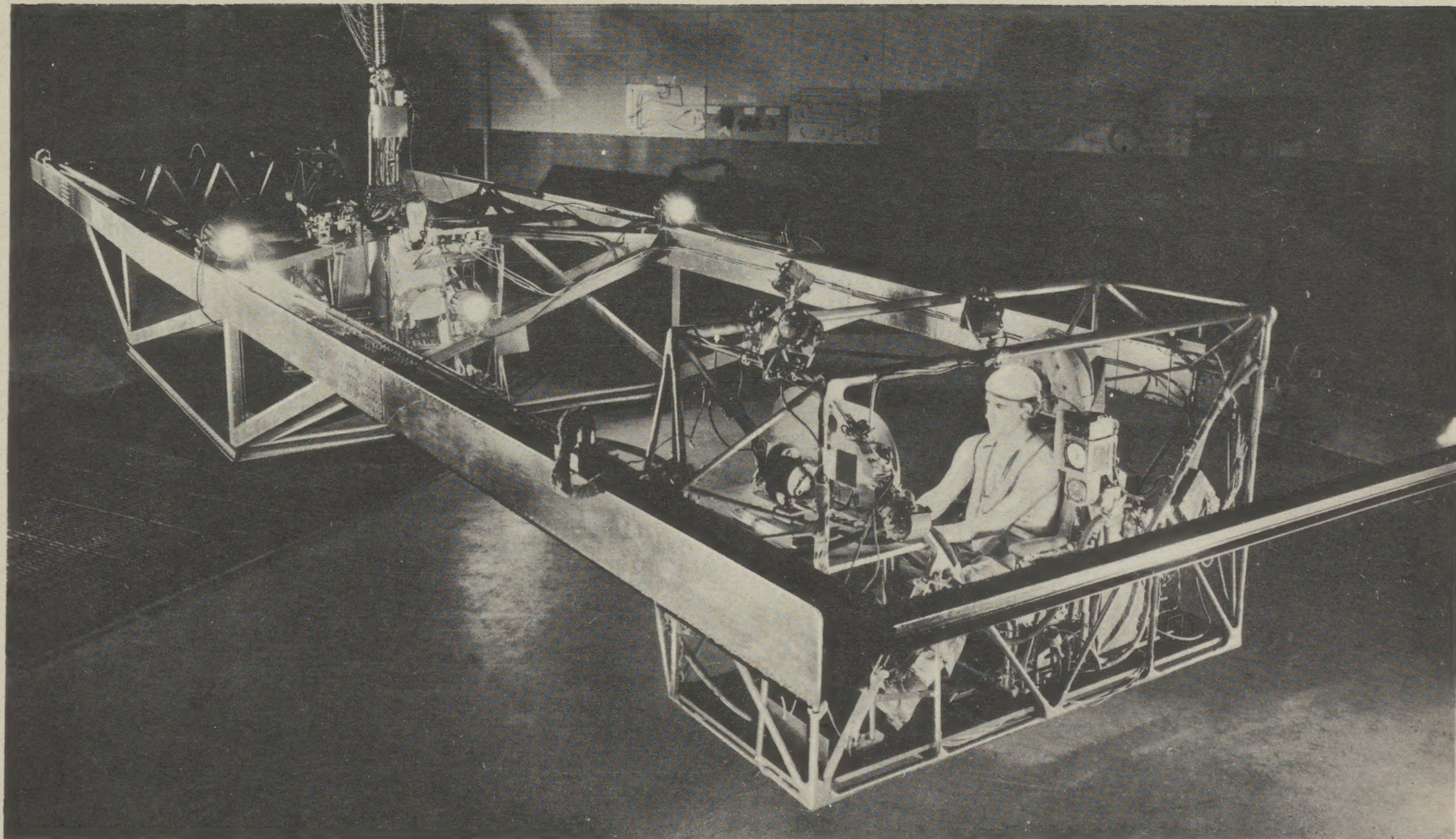
Man readily adjusts himself to his surroundings. The human body constantly makes adjustments for changes in external temperature, for varying amounts of physical activity, for motion in space, for postural changes in relation to gravity, and for changing energy requirements, and adjustments against the inroads of toxic agents and disease. Changes in respiration, in the activity of the sweat glands, in the function of the kidneys, in the ingestion of food, or in the desire for rest or physical activity all tend to maintain the internal environment of the body within very narrow limits of fluctuation.

In aviation, the demands upon the compensatory mechanisms of the body are numerous and of considerable magnitude. The environmental changes of greatest physiological significance involved in flight are (1) marked changes in barometric pressure, (2) considerable variation in temperature, (3) movement at high speed in three dimensions, and (4) change reflected in the mechanical characteristics of the airplane itself.

The advance in aeronautical and mechanical engineering in the past decade has resulted in the development of highly maneuverable airplanes that can cruise at more than 400 miles an hour, climb a mile a minute, and operate effectively at 40,000 feet or higher. Man cannot operate these machines at full capacity without physical aids, such as an artificial supply of oxygen and pressurized equipment, for use at extreme altitudes. Sharp turns or pull-outs from dives at high speed cause centrifugal effects, many times the normal effect of gravity, which lead to unconsciousness if the effects are prolonged.

Man, then, must overcome the handicaps imposed by nature on an organism "designed" for terrestrial life. The necessary aids are largely mechanical. It behooves flyers to understand the mechanical characteristics of their machines and to know the functioning of the human body under the special conditions imposed by flight. In particular, the limiting factors in adjustment of the human body to flight must be appreciated. The extent to which these limiting factors are alleviated by available equipment must be understood clearly. Indifference, ignorance, and carelessness can nullify the foresight, ingenuity, and effort involved in supplying efficient equipment. The ultimate results are failure of missions and unfortunate reactions in personnel.

An effort is made in the following pages to outline some of the important factors in the physiological effects of flight and to describe the devices that contribute to the welfare and tactical efficiency of flying personnel.



Human Centrifuge—Aero Medical Laboratory

CHAPTER I

PHYSICAL CHARACTERISTICS OF THE ATMOSPHERE

Certain physical characteristics of the atmosphere significantly affect the physiological processes of the human body. A brief knowledge of these characteristics is essential in order to understand their importance to the flyer.

Temperatures in the Upper Air

Measurement of the temperatures of the upper atmosphere by means of radio-sonde balloons has been in progress for many years. The highest measurement made thus far was at 22 miles above the earth. On the basis of collected readings of temperatures taken at various latitudes in different parts of the earth, the following generalities may be stated with reasonable reliability:

1. The atmosphere is divided into two spheres: the *troposphere,* which immediately surrounds the earth; and the *stratosphere,* which in turn surrounds the troposphere.

2. The *troposphere* is characterized by a surprisingly constant rate of decrease in air temperature as the height above the earth increases; by turbulent air; and by varying moisture content.

3. The *stratosphere* is characterized by a fairly uniform temperature which varies little with different altitudes; by the almost complete absence of turbulence in the air; and by the absence of moisture.

4. The boundary between the troposphere and the stratosphere is called the *tropopause.*

5. All weather phenomena occur in the troposphere, for they are inherently associated with the physical properties of temperature gradient and moisture content.

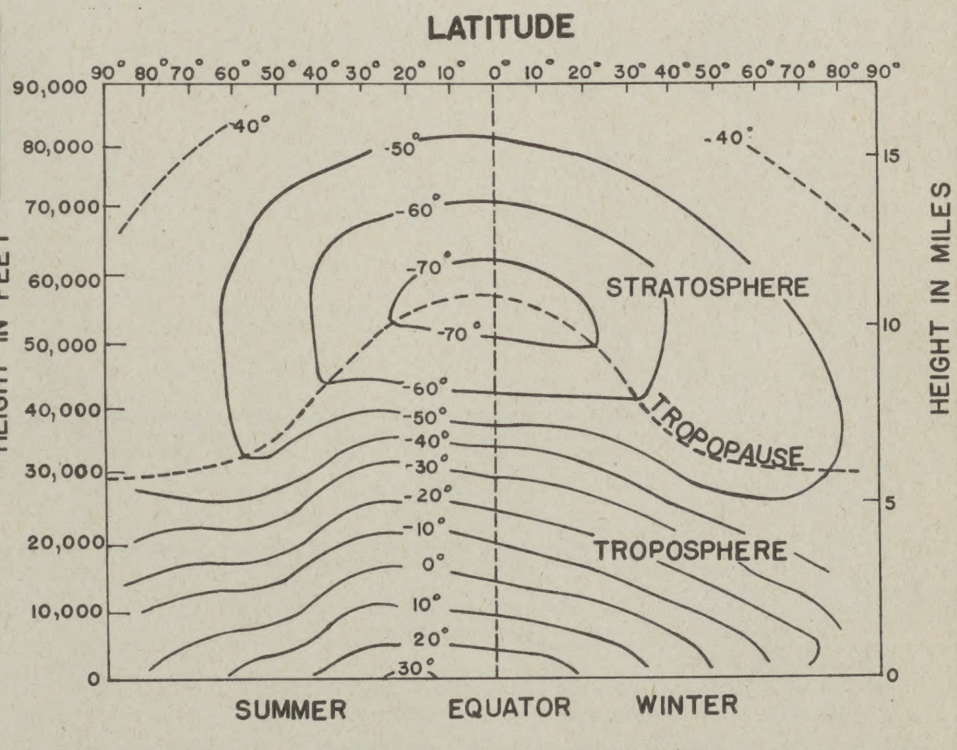
6. The height of the tropopause varies with latitude. It is closest to the earth at the poles (approximately six miles) and farthest away at the equator (approximately 10 miles).

7. The temperature of the stratosphere varies with latitude. The warmest stratosphere temperatures occur over the poles, where temperatures as warm as —40°C (—40°F) may exist. The coldest stratospheric temperatures occur over the equator, where temperatures as low as —80°C (—112°F) have been observed.

8. Over the equator, at still greater heights, reversal of the temperature gradient has been observed.

The preceding facts are presented graphically in figure 1, in which the situation has been somewhat simplified. This figure does not include effects of the oceans and continents, which obviously cause further variation.

Figure 1. — Vertical section through the atmosphere, showing the distribution of mean temperature in degrees centigrade.



The origin of all terrestrial heat is radiation from the sun. With the exception of radiation absorbed by clouds, this radiation is not absorbed in the atmosphere but at the earth's surface. All temperature phenomena in the atmosphere are caused by the presence of water vapor and by absorption of "long-wave" radiation from the earth. Near the earth's surface a body of air can absorb, by radiation from the earth, 11 times the heat it would lose by reradiation to other bodies of air and the heavens. When the temperature of a body of air increases, the air tends to rise. As it rises, it expands because of decreasing atmospheric pressure. When expansion is due to decrease in pressure and not to additional heat, the rising body of air cools, precipitating part of its moisture in the form of clouds. Hence its absorption of heat by radiation from the earth decreases. By repeated cycles of these physical phenomena, commonly known as "weather," relatively constant stratospheric temperatures of approximately —55°C (—67°F) are finally reached, where the water content of a body of air is so low that a balance exists between the absorption of radiation from the earth and reradiation to the heavens. In the stratosphere, therefore, a region of constant temperature is found to exist, regardless of altitude.

Regular changes in atmospheric temperatures from day to night are observed only to a height of approximately 3,000 feet above the ground. In general, temperatures of the upper atmosphere have no diurnal variation. Seasonal variations and variations caused by passing high and low pressure cyclonic areas do change the temperature of the upper air. For example, over San Diego, California, at the 40,000-foot level, atmospheric temperatures in the range of —40° to —80°C (—40° to —112°F) have been observed. Temperatures as low as —80°C are not uncommon at the 40,000-foot level. Temperatures at approximately 20,000 feet above the tropopause, however, usually are very stable the year around.

In general, with increasing altitude, temperatures of the upper air decrease steadily to their constant stratospheric value. Near the equator, however, an increase in temperature is known to exist about 15 miles above the earth. At the latitude of Wright Field, Dayton, Ohio, this temperature inversion probably lies at the 22-mile level. From observations on reflection of sound by the upper atmosphere, it has been calculated that temperatures of the upper air may increase to as high as 177°C (350°F) at the 40-mile level above the earth. This temperature is, for the present, of academic interest only, but for those interested, a speculative graph is presented (fig. 2) in which temperature variations in the extreme upper atmosphere are shown as they are believed to exist.

Inversions of temperature also have been observed near the earth's surface, and at the polar regions this inversion is very pronounced. At Ladd Field, Alaska, ground temperatures of —40° to —45°C (—40° to —49°F) are not uncommon in the winter, while at the same time at the 8,000-foot level temperatures as high as —5°C (23°F) may exist. It is a novel fact that extreme cold (below —40°C) usually is encountered either on the ground or in the stratosphere, but practically never at 10,000 feet, regardless of latitude.

In the physiological sense, the physical property of the upper atmosphere most important to the flyer is the actual pressure of the air in which he flies. Physical well-

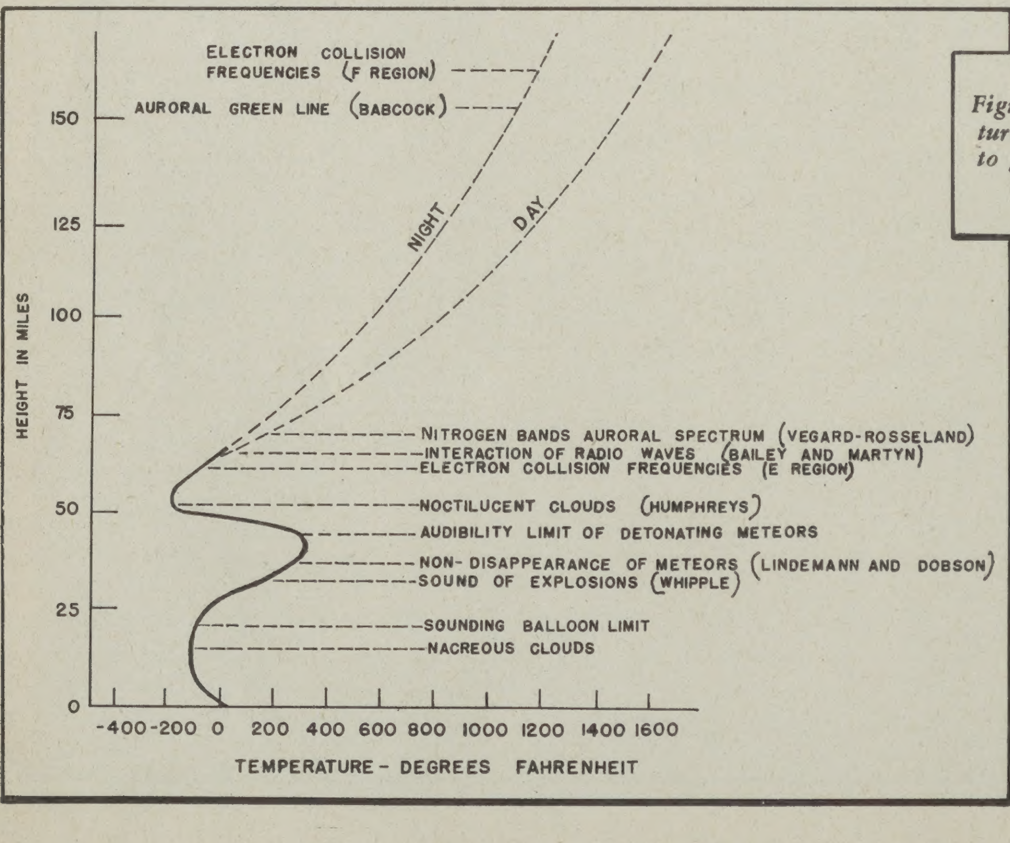


Figure 2. — ***Temperature of the atmosphere to great heights (Martyn and Pulley).***

being and the ability to think and to reason are inherently dependent upon the partial pressure of the oxygen breathed. Unless supplemental oxygen is used, this partial pressure is dependent solely upon atmospheric pressure. Therefore, it is essential that the flyer know the barometric pressure of the level at which he is flying. For this knowledge he must rely upon the altimeter which, by means of a calibration factor, describes a given pressure in terms of feet.

Because it is convenient to describe pressure in terms of feet, it is important to understand the basis for the present calibration of the Army Air Forces altimeter and to understand how the three technical altitudes familiar to all pilots, "pressure," "density," and "tapeline" altitudes, are related to each other and to physiologic well-being.

The United States Standard Atmosphere

The calibration of an altimeter is the problem of interpreting in feet or meters a given pressure in millimeters or inches of mercury. The pressure of the air at any level is a relatively simple measurement, but its calibration in feet is mainly theoretic. The theorem of LaPlace states that, for a column of air which is of uniform temperature and infinite height and which is subjected to the field of gravity, at any point the height varies linearly with the logarithm of the pressure. By assuming an appropriate constant and a uniform temperature of 15°C (59°F) for the column, a calibration between pressure and altitude can be constructed. The assumption that the column of air is of uniform temperature in itself is invalid and leads to altitude values in feet which are considerably higher than those found by actual methods of survey from the ground.

In 1924 the Weather Bureau, in conjunction with the Bureau of Standards, determined the present United States Standard Atmosphere. Experimentally it was found that at a latitude of 40 degrees in the United States, temperature decreased linearly with altitude until the

TABLE I

SOME PROPERTIES OF U. S. STANDARD ATMOSPHERE (TAKEN FROM N. A. C. A. REPORTS, NO. 218 AND NO. 538)

Altitude	*Pressure*		*Temperature*		*Density ratio*
Feet	*Mm of Hg*	*Lb per sq in*	*C*	*F*	
0	760.0	14.69	15.0	59.0	1.000
2000	706.6	13.67	11.0	51.9	.9428
4000	656.3	12.69	7.1	44.7	.8881
6000	609.0	11.78	3.1	37.6	.8358
8000	564.4	10.91	— 0.8	30.5	.7859
10000	522.6	10.11	— 4.8	23.3	.7384
12000	483.3	9.35	— 8.8	16.2	.6931
14000	446.4	8.63	—12.7	9.1	.6499
16000	411.8	7.96	—16.7	1.9	.6088
18000	379.4	7.34	—20.7	— 5.3	.5698
20000	349.1	6.75	—24.6	—12.3	.5327
22000	320.8	6.20	—28.6	—19.5	.4947
24000	294.4	5.69	—32.5	—26.6	.4640
26000	269.8	5.22	—36.5	—33.7	.4323
28000	246.9	4.77	—40.5	—40.9	.4023
30000	225.6	4.36	—44.4	—48.0	.3740
32000	205.8	3.98	—48.4	—55.1	.3472
34000	187.4	3.62	—52.4	—62.3	.3218
35332	175.9	3.41	—55.0	—67.0	.3058
36000	170.4	3.30	—55.0	—67.0	.2962
38000	154.9	3.00	—55.0	—67.0	.2692
40000	140.7	2.72	—55.0	—67.0	.2447
42000	127.9	2.47	—55.0	—67.0	.2224
44000	116.3	2.25	—55.0	—67.0	.2021
46000	105.7	2.04	—55.0	—67.0	.1838
48000	96.05	1.86	—55.0	—67.0	.1670
50000	87.30	1.69	—55.0	—67.0	.1518
52000	79.34	1.53	—55.0	—67.0	.1379
54000	72.12	1.39	—55.0	—67.0	.1254
56000	65.55	1.27	—55.0	—67.0	.1140
58000	59.58	1.15	—55.0	—67.0	.1036
60000	54.15	1.05	—55.0	—67.0	.0941

height of about 35,000 feet was reached, at which altitude the temperature became constant with altitude. With this experimental fact as a basis, the United States Standard Atmosphere is founded on the following assumptions:

1. Temperature decreases linearly with altitude until the isothermal atmosphere begins, the gradient vanishing at the lower limit of the isothermal atmosphere, that is, at 35,332 feet.

2. The temperature of the isothermal atmosphere is —50°C (—67°F).

3. The air is dry.

4. The air is a perfect gas.

5. Gravity is constant at all altitudes.

Some physical properties of the United States Standard Atmosphere are given in table 1, in which altitudes extending up to 60,000 feet are presented. At sea level the standard pressure and temperature are 760 mm (29.92 inches) of mercury and 15°C (59°F). The temperature decreases at a uniform rate of about 19.8°C (67.6°F) for each 10,000 feet in altitude until an altitude of 35,332 feet is reached, at which level the isothermal atmosphere with a temperature of —55°C (—67°F) begins. For each altitude in feet, the corresponding pressure in millimeters of mercury is given. This relationship is the official calibration curve for all altimeters in current use in all AAF aircraft, but it is not used internationally.

If the atmosphere at any given point meets conditions specified in the definition of the United States Standard Atmosphere, the altimeter indicates density or tapeline altitude above sea level. These conditions rarely exist, since temperature varies considerably. For navigational purposes the flyer is interested only in tapeline altitude and must correct his altimeter reading for temperature. The "Aero Dead Reckoning Slide Rule—Dalton Model B" is used to obtain approximate tapeline altitude if the altimeter reading (Kollsman dial at 29.92) and outside temperature are known. Tapeline altitude may be estimated by adding 100 feet for every degree centigrade above the temperature of the standard atmosphere at a given altimeter reading. Similarly, when the temperature is lower than standard, 100 feet should be subtracted for every degree centigrade.

Corrected altimeter reading is significant also in the study of aerodynamic performance of airplanes. The corrected value provides a more accurate measure of the density of the atmosphere, and it is density which determines pull of propellers, lift of wings, and similar factors in performance. A comparison of tapeline or density altitude with pressure altitude and air temperature is given in table 2.

In preparing to land, the pilot is not as much concerned with altitude above sea level as with altitude above the ground. The altimeter may be set to indicate this altitude if atmospheric pressure at the field is known and is radioed to the flyer as the "Kollsman number."

TABLE 2

THE RELATIONSHIP OF DENSITY ALTITUDE TO PRESSURE ALTITUDE AND AIR TEMPERATURE: TYPICAL EXAMPLES

Density altitude, feet	*Temperature °C*	*Pressure altitude feet*
20,000	12	16,665
	—10	18,600
	—30	20,500
	—50	22,530
30,000	—20	27,730
	—40	29,575
	—60	31,520
35,000	—30	32,755
	—50	34,595
	—70	36,500
40,000	—30	37,700
	—50	39,500
	—70	41,500

When the small scale on the altimeter is set to this number the altimeter indicates altitude above ground level.

Flyers who participate in high-altitude flights should understand that all criteria for the use of oxygen equipment and the probability of their having "bends" and anoxia depend on the actual reading of the altimeter in the airplane and not on the true height above sea level. Distinguishing between pressure and density or tapeline altitude is important to the physiologist and the Flight Surgeon in interpreting flyers' records in the range of 35,000 to 45,000 feet. In this range, the physiological response of the human body changes rapidly with slight changes in altitude. The following facts should be remembered:

1. Aerodynamically, airplane performance is judged in terms of density or tapeline altitude.

2. Physiologically, human performance is judged by the pressure altitude which is shown by the actual reading on the altimeter (with Kollsman dial set at 29.92).

The Role of Moisture in Flight

Except for its nuisance effect on the complacency of the pilot, atmospheric moisture is unimportant in the physiology of flight. However, the moisture phenomenon of fogging and frosting of windows is worth mention. On ascent this can be avoided by proper ventilation of the airplane, but on descent from high altitudes, the cold interior metal surface may become covered with heavy dew. If re-ascent is made the dew may freeze on the interior of the windows and seriously impair vision.

CHAPTER II

RESPIRATION AND CIRCULATION AT ALTITUDE

The Respiratory System

The most significant stresses placed upon the body by altitude are due to lowered temperature and lowered barometric pressure. Reduced barometric pressure has two effects: lowering of oxygen pressure, and lowering of total pressure on the body. The reduced pressure of oxygen is the most deleterious because it begins to have an appreciable effect at relatively low altitudes; it has the same effect on all flyers within a relatively narrow range of individual variation; and its effects may rapidly produce unconsciousness and death. The significance of low temperature and lowered total pressure will be discussed later.

Respiration commonly is called "breathing." However, it may be defined more explicitly as "the exchange of gases between an organism and its environment." In the case of all animal organisms, respiration consists principally of the exchange of oxygen and carbon dioxide. Oxygen is taken into the body and utilized to burn the food from which energy is derived to operate the entire mechanism necessary to keep the body alive and active. The oxidized gaseous product of this combustion, principally carbon dioxide, then is eliminated, completing the process known as "respiration." This exchange of gases takes place continuously throughout the life span of an organism, from conception to death.

From a physiological point of view, respiration in the body of man may be considered under two divisions:

1. *External respiration,* which involves the exchange of gases between the blood in the capillaries of the lungs and the external atmospheric environment as represented by air in the air sacs of the lungs. This presentation of the subject of respiration is concerned chiefly with the principles of external respiration.

2. *Internal respiration,* which is the exchange of gases between the body's tissue cells and the blood as the blood passes through the minute capillaries which permeate every tissue in the body.

The processes by which gases are exchanged between the lungs and the blood and between the blood and the tissues do not differ qualitatively in a normal individual. In the first instance, oxygen diffuses from the lungs into the blood; in the second, it passes from the blood into the cells.

Structure of the Lungs.—Since the exchange of gases in external respiration takes place in the lungs, knowledge of the anatomy of the lungs and of the physical and chemical principles involved in the exchange of gases within them is desirable. No detailed description of the gross anatomy of the lungs will be given. The structure of the final division of the lungs, namely the

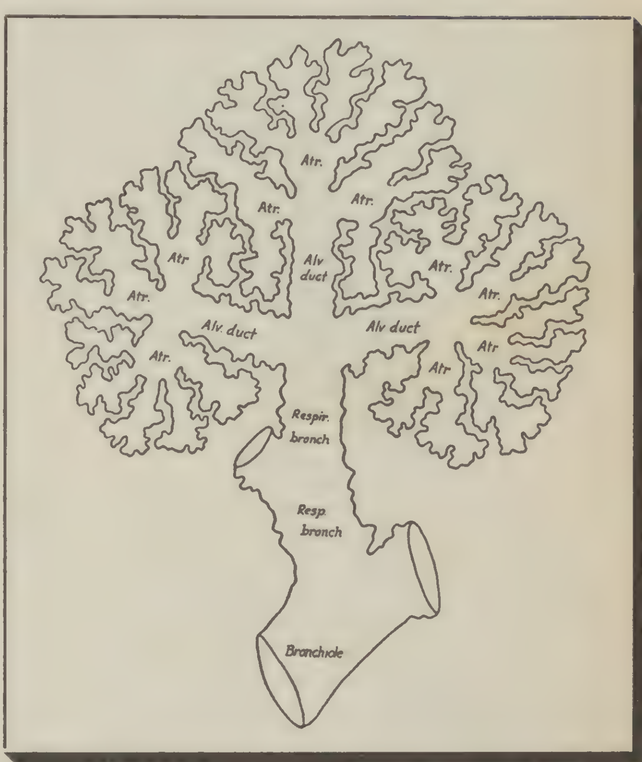


Figure 3.—Arrangement of three lung lobules of the cat, showing their respiratory bronchioles, alveolar ducts, atria, and air sacs (after Miller, W. S.: The air spaces in the lung of the cat. J. Morphol. 24:459-485, [Dec.] 1913).

alveoli, or air sacs, is shown in figure 3. The alveoli form the functionally important part of the respiratory tract; it is within them that the exchange of gases between the body and the environment takes place. Each alveolus, of which there are several million in the average human lung (figure 4), is approximately 1/25 inch in diameter. The total surface area of all the alveoli in the human lung has been estimated to be between 700 and 800 square feet, which is 40 to 50 times the surface of the skin of the body. The walls of these alveoli are moist and extremely thin, being only about 1/50,000-inch thick. Each alveolus is surrounded by a network of capillaries through which blood flows at all times. It is the gaseous exchange between the blood in the capillaries and the air in the alveoli that is of utmost importance to the body. Although this exchange of gases must take place through two membranes, the alveolar wall and the capillary wall, these membranes are so thin that they offer no appreciable resistance to the transfer of dissolved gases. Actually, the blood remains in the capillaries of the lungs only one or two seconds, a sufficient

Figure 4.—A portion of the human lung after metallic injection and removal of tissues by corrosion. Bronchioles and alveolar ducts are shown, with clusters of alveoli arising from the ducts. (Magnified 15X.) Courtesy Dr. A. H. Bulbulian, Mayo Clinic.

time for the necessary exchange of gases to be accomplished.

MECHANICS OF BREATHING.—The flow of gases to and from the alveoli is a mechanical process. The lungs lie completely enclosed within the cavity of the chest. The sides of the chest cavity are rendered rather rigid by the ribs. The diaphragm, a partition composed of muscle, lies below. The chest cavity is constructed in such a manner that its total volume can be increased or decreased by muscular activity which raises or lowers the ribs and by contraction and relaxation of the diaphragm. Since the chest is a closed cavity with only one opening to the outside, the trachea, changes in chest size ventilate the air spaces in the lungs. *(See fig. 5.)* Inspiration is the active phase of this process; expiration is largely a passive phenomenon resulting from relaxation of muscles.

Respiratory Cycle.—The average man when at rest expands the chest at each inspiration to an extent which draws into the lungs and respiratory passages about 500 cc (30 cubic inches) of air. Approximately the same volume of air is expelled with each expiration. This process is repeated about 12 to 16 times a minute in most individuals, although a few normal persons breathe as infrequently as five times per minute.

The volume of air inhaled and exhaled with each breath is called the "tidal volume." The volume of air inhaled (and exhaled) per minute can be determined by multiplying the tidal volume by the number of breaths per minute. The volume of air breathed per minute is termed the "ventilation rate" and in the average individual at rest amounts to 6 to 8 liters (500 cc x 12 to 16 breaths per minute=6,000 to 8,000 cc=6 to 8 liters per minute).

The ventilation rate, adjusted to the needs of the body, is increased greatly by work. Figure 6 shows the relationship between ventilation rate and work rate at altitudes up to 40,000 feet, with subjects breathing 100 percent oxygen. It should be noted that the ventilation rate does not change with altitudes up to 30,000 feet. The increased ventilation rate at 40,000 feet is caused by the decreased pressure of oxygen in the blood. Measurements of ventilation rates of bomber crews and pursuit pilots during flight showed an average range of 7.3 to 26.5 liters per minute during periods of inactivity, the average rate being 13.9 liters per minute. When the subjects were active, their rates ranged from 6.3 to 64 liters per minute, with an average of 24.8 liters. The highest ventilation rate was that of the waist gunner. Those of the other subjects decreased in the following order: tail gunner, nose gunner, bombardier, top turret gunner, pursuit pilot, bomber pilot, and copilot.

The volume of air which can be exhaled from the lungs after the deepest possible inhalation is termed "vital capacity" and represents the maximum value to which the tidal volume might be increased. These facts are illustrated diagrammatically in figure 7.

Of the 500 cc taken into the respiratory system with each inspiration, the last 140 or 150 cc never reach the alveoli, for this is the volume of air necessary to fill the respiratory passages leading from the nose to the alveoli. It is the first air to emerge on exhalation, and, when analyzed, its gaseous composition has not changed appreciably from that of outside air. The remainder of the tidal air mixes with the gases in the alveoli. The composition of alveolar air ordinarily remains very constant at ground level.

During a single inspiration of a resting individual, the instantaneous flow rate increases from zero at the beginning to 20 or 30 liters per minute near the midpoint of inspiration and returns to zero at the end. Thus, although the minute-volume ventilation of such an individual may be only six to eight liters per minute, the maximal instantaneous inspiratory peak flows will be as high as 20 to 30 liters per minute. Likewise, an individual who is exercising moderately may have a minute-volume ventilation of only 25 to 45 liters per minute and an instantaneous flow rate as high as 65 to 90 liters per minute. In general, minute-volume ventilation (stated at standard conditions of temperature and pressure) may be multiplied by approximately 3.7 when the subject is at rest and 2.8 when the individual is exercising to obtain the maximal inspiratory (peak) flow rates. Curves showing the inspiratory flows of an individual at rest and immediately after exercise are presented in figure 8.

The argument often advanced is that since the maximal inspiratory flow rate is of such short duration and is actually only a peak in inspiration, it should be of minor consideration in the design of oxygen regulators. Nevertheless, if an analysis is made of the inspiratory curves of any individual, it can be shown that a considerable por-

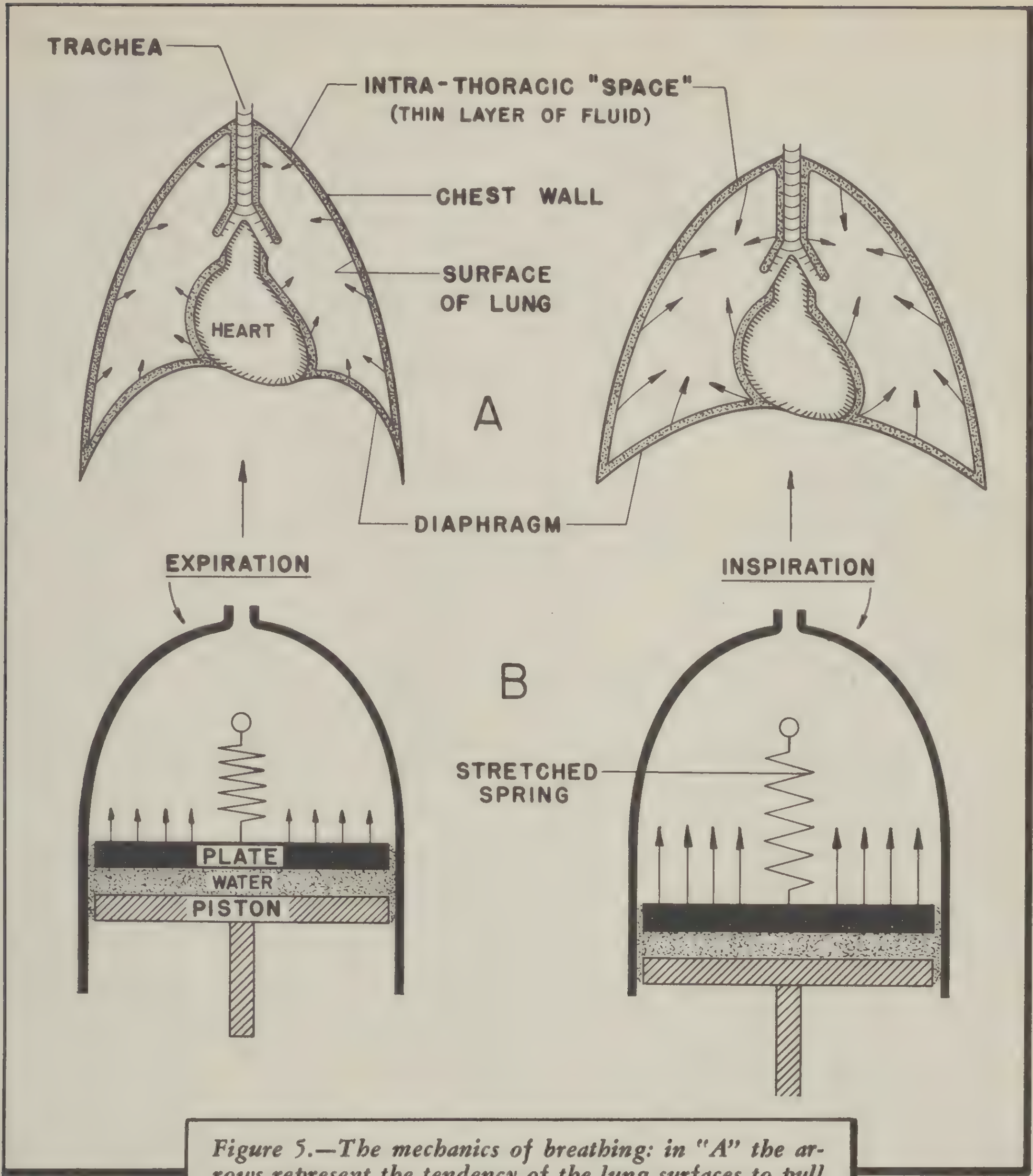


Figure 5.—The mechanics of breathing: in "A" the arrows represent the tendency of the lung surfaces to pull away from the chest wall. The lengths of the arrows represent the degrees of that pull. The intrathoracic space (the space between the tissue of the lungs and the chest wall) is filled with a thin layer of fluid. The lung surfaces remain in contact with this layer of fluid and the lungs expand and contract as if they were a part of the chest wall itself. In "B" is illustrated how INSPIRATION is the active phase of the respiratory cycle, the piston pulling against a spring and drawing in air. The expiratory phase occurs as the result of recoil of the spring when the piston is released. The elasticity of the chest wall makes possible a rapid elastic recoil of the lungs. (Redrawn from Carlson and Johnson: The Machinery of the Body.)

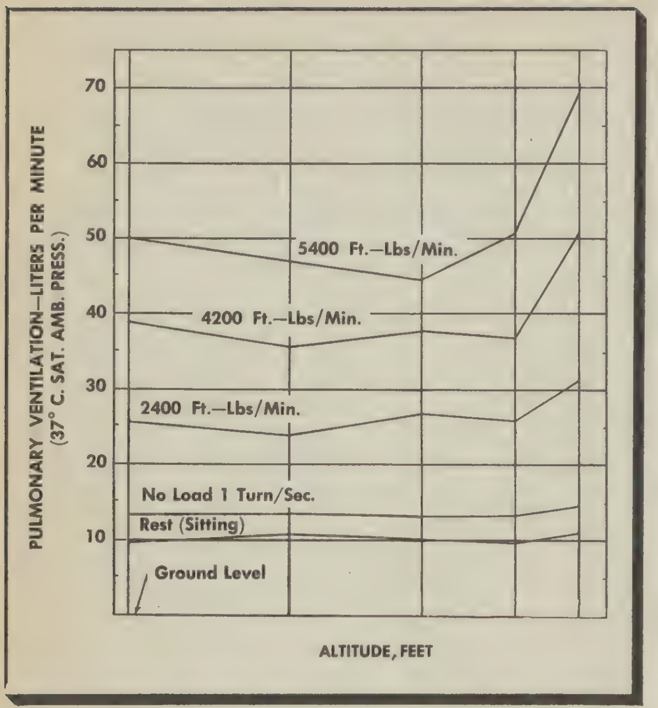


Figure 6.—Relationship between pulmonary ventilation and simulated altitudes at various levels of activity. Subjects breathing 100 percent oxygen.

tion of the tidal volume is delivered at flows just under peak flow. *(See figure 9.)* It is shown that during rest 55 percent, and during moderate exercise 53 percent, of the tidal volume is delivered at or above 80 percent of the peak flow. Furthermore, a significant portion of the tidal volume of some individuals may be delivered at relatively low flows. Thus, demand oxygen regulators must be constructed to deliver oxygen smoothly (without excessive suction pressure for opening) at these low rates of flow.

Any successful oxygen equipment for flying personnel must meet the maximal flow demanded without necessitating an uncomfortably great inspiratory effort on the part of the person using the equipment. For this reason, a knowledge of the magnitude of maximal inspiratory flows during rest and moderate exercise is of considerable importance in the design of oxygen equipment.

COMPOSITION OF RESPIRED AIR.—The exchange of respiratory gases between air in the lungs and blood as it passes through the capillaries follows those physical laws which govern the behavior of gases in general.

Atmospheric air on a dry basis and by volume is 20.94 percent oxygen, 79.02 percent nitrogen, and 0.04 percent carbon dioxide. Included with the nitrogen are small amounts of rare gases which are of no physiological significance. The relative composition of dry atmospheric air does not vary appreciably with altitude up to 70,000 feet. There are no significant variations with latitude.

Percentage Versus Partial Pressure.—To express gas quantities by their percentages of the atmosphere means very little when variations in altitude are involved. Percentile figures show only the relative volume of gases, and not their molecular concentrations which determine the availability of any gas to the body. The actual concentration of any gas can be expressed better in terms of

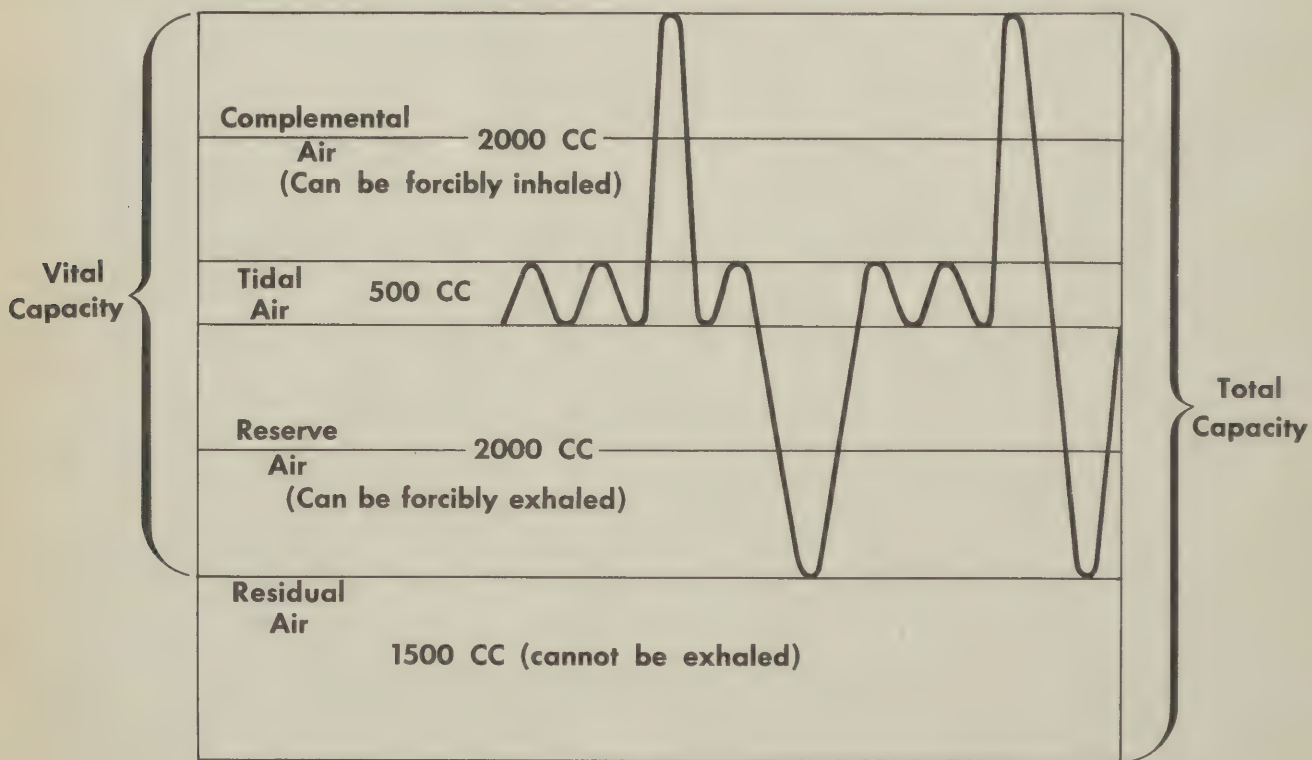


Figure 7.—Various subdivisions of the air in the lungs.

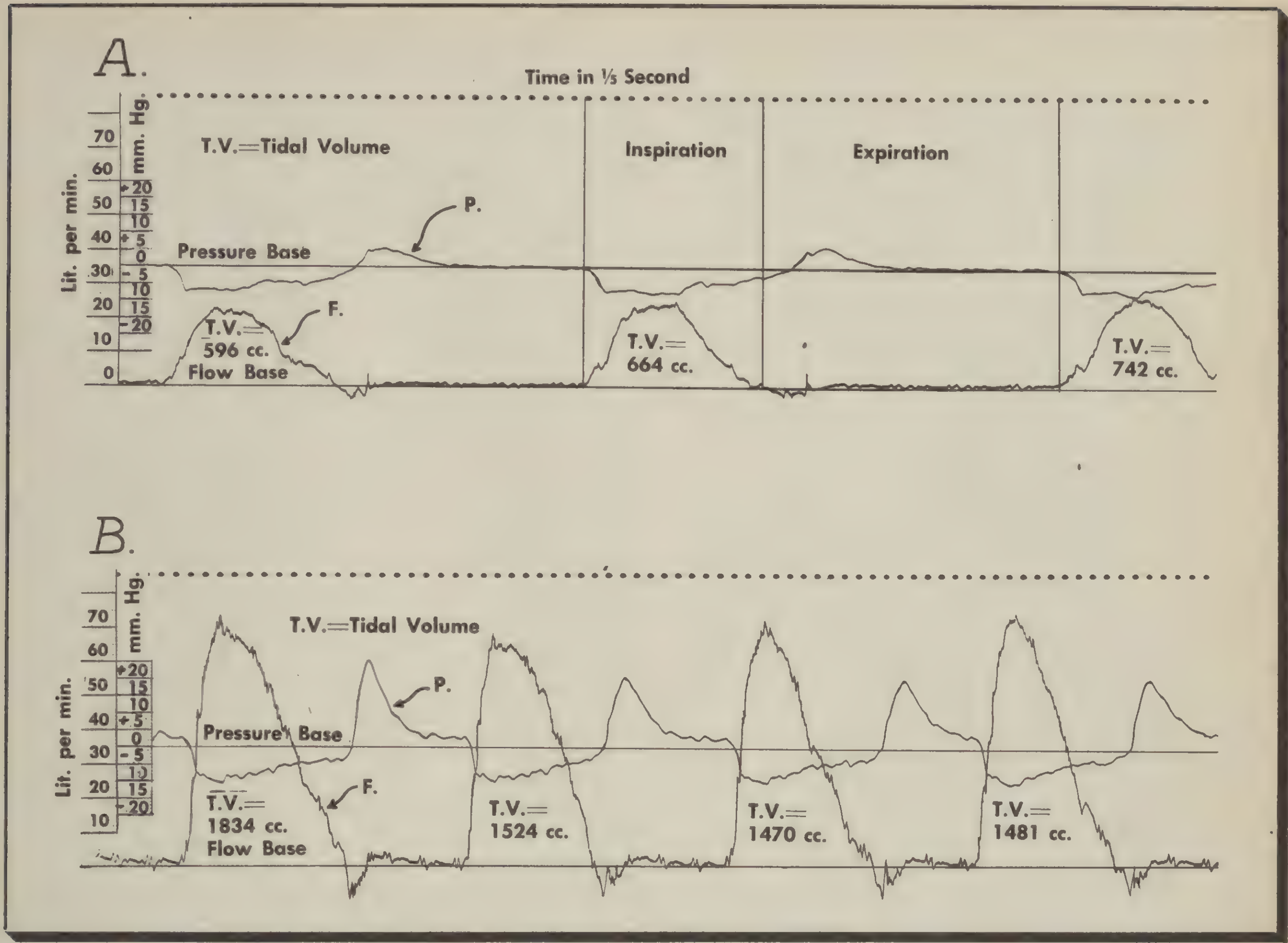


Figure 8.—Inspiratory flow during rest (A) and immediately after exercise (B). The column on extreme left indicates liters per minute instantaneous flow.

its *partial pressure*. To understand partial pressure, it is necessary first to understand *total pressure*.

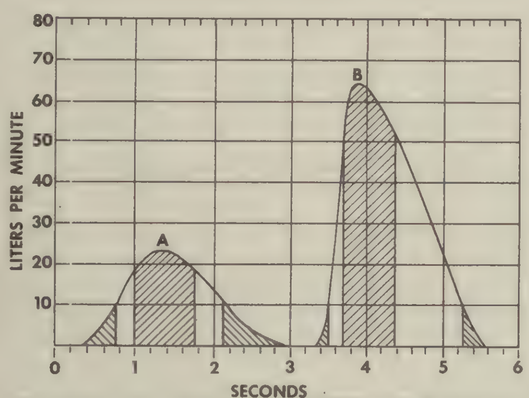
Total Pressure.—A quantity of gas, when mixed with other gases, exerts the same pressure that it would if the other gases were not present. The total pressure of a mixture of gases is, therefore, the sum of the pressures of the individual gases comprising the mixture. For example, the total pressure (barometric pressure) of the atmosphere at sea level is 760 mm Hg (14.7 psi). This total pressure is the simple sum of all the individual (partial) pressures exerted by the various gases comprising the atmosphere.

Partial Pressure.—Assuming that the air is dry, the pressure exerted by oxygen at sea level is

$$\frac{20.94}{100} \times 760 = 159 \text{ mm Hg } (3.1 \text{ psi}).$$

The pressure exerted by nitrogen at sea level is, similarly,

$$\frac{79}{100} \times 760 = 601 \text{ mm Hg } (11.6 \text{ psi}).$$



A		B	
CC	%	CC	%
Tidal volume		Tidal volume	
647.0	100.0	1533.0	100.0
Volume inspired at Velocities above 80% of Peak Velocity			
358.0	55.4	812.0	53.0
Volume inspired below 10 Liters per Minute			
112.0	17.3	35.0	2.3

Figure 9.—Relation between tidal volume and inspiratory flow during rest (A) and with exercise (B).

The partial pressure of oxygen is 159 mm Hg; that of nitrogen is 601 mm Hg. Together they form the total atmospheric pressure of 760 mm Hg at sea level and include a small percentage of carbon dioxide and other, rare gases in the atmosphere.

At an altitude of 18,000 feet the atmospheric pressure is 380 mm Hg (7.4 psi), or one-half the pressure at sea level, which means that half the total mass of the atmosphere is below 18,000 feet. The percentage of oxygen in the atmosphere at an altitude of 18,000 feet is 20.94 but, since the partial pressure of oxygen at this altitude is half that at sea level, the amount of oxygen which is available to the body is greatly reduced. The partial pressure of oxygen at 18,000 feet is

$$\frac{20.94}{100} \times 380 = 79.5 \text{ mm Hg } (1.5 \text{ psi})$$

—half the partial pressure of oxygen at sea level. At 27,000 feet the atmospheric pressure is one-third its value at sea level; at 33,400 feet, it is one-fourth its sea level value, and at 38,500 feet it is one-fifth its sea level value.

The quantity of gas which goes into solution (temperature remaining constant) is proportional to the partial pressure of the gas concerned. For example, in a person breathing atmospheric air, approximately half as much oxygen or nitrogen is physically dissolved in blood plasma at 18,000 feet as is physically dissolved at sea level. This fact is significant in considering both the problem of oxygen want at high altitudes and the problems related to aeroembolism.

The Respiratory Gases.—The atmospheric air that is breathed contains variable amounts of water vapor, but as soon as air is drawn through the nasal passages into the trachea, it becomes saturated with water vapor. Therefore, the approximate partial pressures of the respiratory gases as they enter the lungs at sea level are as follows: oxygen, 149; nitrogen, 564; water vapor, 47; and carbon dioxide, 0.3 mm Hg. When air is drawn into the lungs, it mixes with that already in the lungs which is lower in oxygen and higher in carbon dioxide content than the inspired air. Therefore, samples of expired air, when analyzed, contain less oxygen and more carbon dioxide than does inspired air. Naturally, expired air does not give a true picture of the conditions that exist in the alveoli, since it is a mixture of air from both the alveoli and the trachea. The partial pressure of oxygen in the alveoli is the significant factor for the body, for it is this pressure that determines how much oxygen reaches the blood. In table 3 are shown the partial pressures of the gases in the alveoli at sea level and at various altitudes. It should be noted that the partial pressure of oxygen in the alveoli at 34,000 feet, when a man is breathing pure oxygen, is the same as that at sea level when he is breathing air. At an altitude of 40,000 feet the partial pressure of oxygen is greatly reduced. At altitudes of more than 40,000 feet the partial pressure of oxygen decreases rapidly and falls below the limit which permits enough oxygen to be absorbed by the blood to maintain the body in a physiologically safe condition.

ANOXIA AT HIGHER ALTITUDES.—Breathing 100 percent oxygen at 34,000 feet will produce an alveolar oxygen tension equal to that produced by breathing air at sea level. At about 34,000 feet, however, the partial pressure of oxygen in the lungs begins to fall below its sea-level value, even though pure oxygen is breathed.

The partial pressures of oxygen, carbon dioxide, and water vapor in the lungs are given in table 3. Whereas the oxygen pressure in the alveoli varies with the percentage of oxygen in the inspired air and the total barometric pressure, and consequently is subject to variation as either of these two factors change, the partial pressures of carbon dioxide and water vapor in alveolar air show a remarkable tendency to constancy. Alveolar carbon dioxide tension remains at approximately 40 mm Hg without regard to altitude, and alveolar water vapor maintains a constant pressure of 47 mm Hg. As the total pressure in the lungs falls with increasing altitude, the carbon dioxide and water vapor in the lungs attain a proportionately larger volume at the expense of oxygen and nitrogen. Hence, at sea level, carbon dioxide and water vapor, possessing a combined pressure of 87 mm Hg, take up $\frac{87}{760}$ of the total volume in the lungs. At 18,000 feet, where the total pressure is reduced by one-half, the proportionate lung volume of these two gases is equal to

$$\frac{87}{380}\text{; at 27,000 feet, }\frac{87}{253}\text{; at 38,000 feet, }\frac{87}{152}.$$

and so on. The progression leaves less and less "room" for oxygen and nitrogen, so that a point is finally reached at which it is impossible, even breathing 100 percent oxygen (eliminating nitrogen), to maintain a molecular concentration of oxygen in the lungs adequate to sustain consciousness, or even life. At 50,000 feet, for example, where the total atmospheric pressure

TABLE 3

THE COMPOSITION AND PARTIAL PRESSURES OF ALVEOLAR AIR AT SEA LEVEL AND AT VARIOUS ALTITUDES

Alveolar gases	*Breathing Air at sea level*	*Breathing Pure Oxygen at altitude (feet)* 30,000	34,000	40,000
	Millimeters of mercury (mm Hg)			
Oxygen	100	138	100	57
Carbon dioxide	40	40	40	38
Nitrogen	573	0	0	0
Water vapor	47	47	47	47
Total pressure	760	225	187	142

is 87 mm Hg, alveolar carbon dioxide and water vapor tension actually represent the total pressure.

In order for an individual to get along at altitudes in excess of 40,000 feet, therefore, he must resort to pressure breathing or remain confined in a pressurized cabin. The effect of either of these methods, each in its own way, is to increase the total pressure in the lungs, thereby permitting the maintenance of an adequate alveolar oxygen tension.

THE EXCHANGE OF GASES IN THE LUNGS.—The method by which gases are acquired by the blood has been the subject of much study by physiologists for a long time. Present-day knowledge indicates that the exchange of gases between the lungs and the blood takes place by means of physical diffusion and that it follows the fundamental physical laws governing gases. Gases diffuse from regions of higher partial pressure to those of lower partial pressure. This is proved by experiments in which samples of arterial blood are analyzed for their gaseous content and are compared with the composition of gas in the lungs. Samples of arterial blood can be obtained easily at ground level but are difficult to take at high altitudes. Such has been accomplished, however, and figure 10 shows the percentile saturation of blood with oxygen at altitudes up to 44,800 feet while subjects were breathing pure oxygen.

CONTROL OF BREATHING.—Normal breathing, though to a certain extent under voluntary control, is essentially an involuntary act. Regulation of respiratory movements is accomplished at low altitudes by responses of the nervous system to the concentration of *carbon dioxide* in the blood rather than to that of *oxygen.* The origin of nerve impulses affecting frequency and depth of respirations is in the *respiratory center* of the medulla oblongata. When the content of carbon dioxide in the blood increases, as it does during exercise, the respiratory center is stimulated and nerve impulses are sent out which increase the rate and depth of respiration. At altitudes of more than 10,000 feet without supplementary oxygen, and at altitudes of more than 40,000 feet with 100 percent oxygen, the reduction in the amount of oxygen in the blood is generally sufficient to cause an increase in the rate and depth of breathing by stimulating the carotid body. *(See figure 11.)*

The increase in ventilation rate that can be achieved by this mechanism, however, is considerably less than the maximum achieved through the medium of an increase in the carbon dioxide content of the blood.

Under ordinary circumstances and at ground level, this relative insensitivity of the respiratory control mechanism to anoxia imposes no undue hardship on the person affected, because as the need for oxygen in the cells of the body becomes greater (for example, during exercise), the output of carbon dioxide by the cells likewise increases. The amount of carbon dioxide carried by the blood is larger, the respiratory control mechanism is stimulated, and the ventilation rate is increased to accomplish elimination of the carbon dioxide. The more rapid rate of ventilation increases the amount of oxygen brought into the alveoli of the lungs and, thus, made available for absorption by the blood. It is only because of the close parallel between the *rate of production* of carbon dioxide and the *need for oxygen* by the tissues of the body that various oxygen requirements are so well met at ground level.

At high altitudes the situation is very different. The partial pressure of oxygen is lowered without any cor-

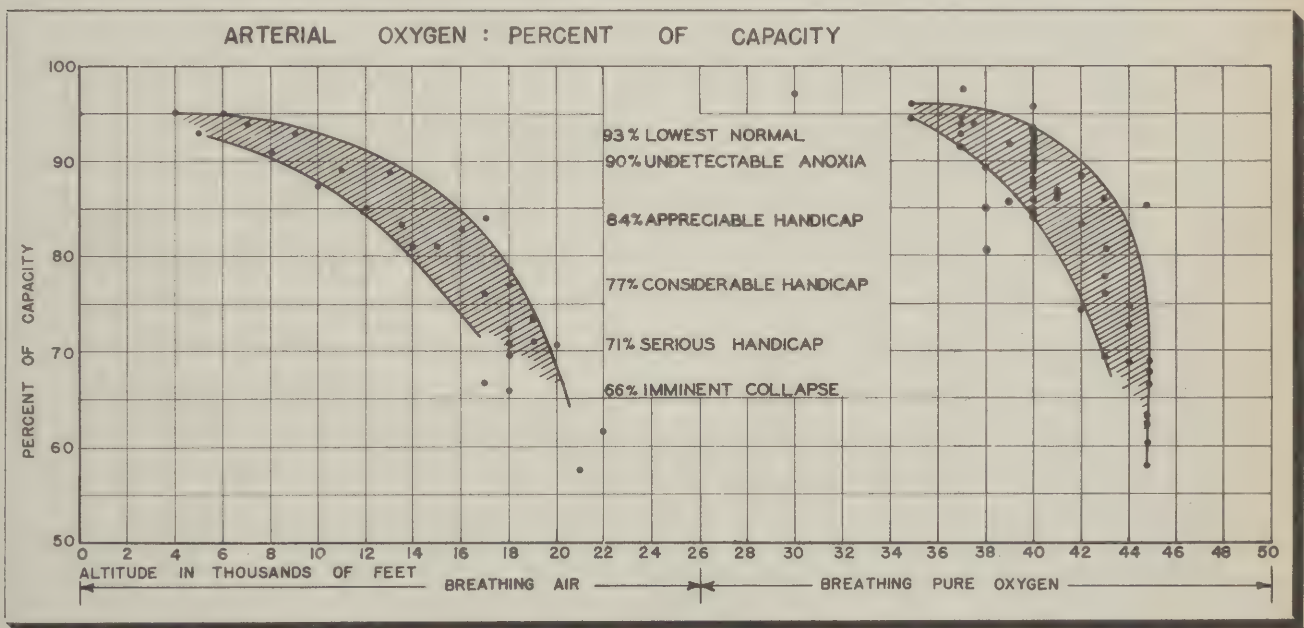


Figure 10.—Percentile saturation of arterial blood at altitudes up to 44,800 feet, with subjects breathing pure oxygen. The curves on the left show the range of performance among persons breathing air. Curves on the right show the range of performance among persons breathing pure oxygen.

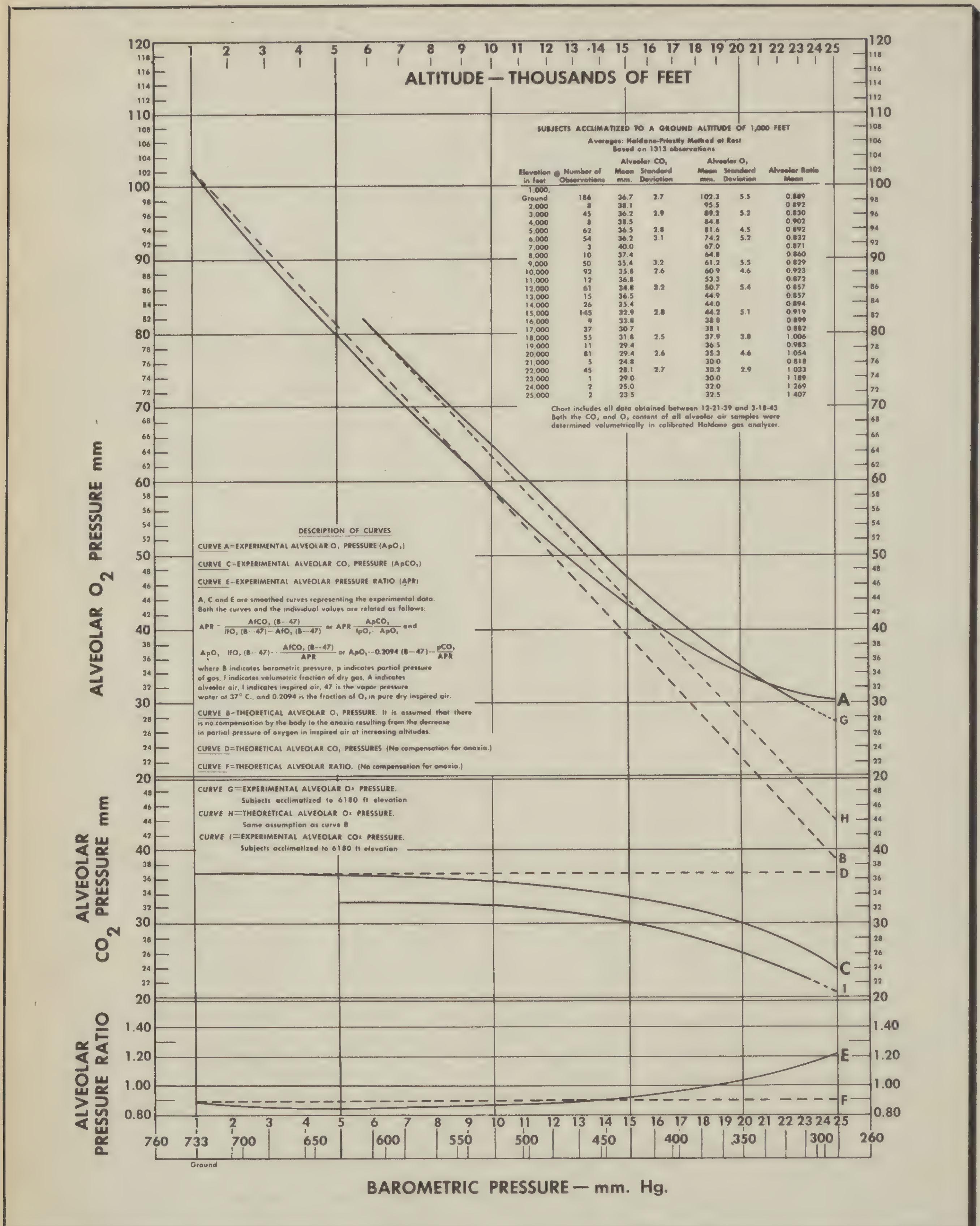


Figure 11.—Alveolar oxygen and carbon dioxide pressures, and alveolar ratios at various altitudes while breathing air. (Redrawn from Chart of Mayo Aero Medical Unit, Walter M. Boothby, October, 1943.)

responding increase in carbon dioxide. Therefore, the body fails to make the response required, namely, an adequately increased ventilation rate. At altitudes between 12,000 and 15,000 feet, the oxygen tension in the blood falls low enough to stimulate the carotid body, producing a reflex rise in ventilation rate. Actually, however, this increase is inadequate. In addition, it is of limited value to the body, since under such circumstances it produces a greater loss of carbon dioxide, excessive loss of which produces dizziness, tingling of the extremities, and, if continued long enough, tetanic spasms of the limbs, and, finally, unconsciousness.

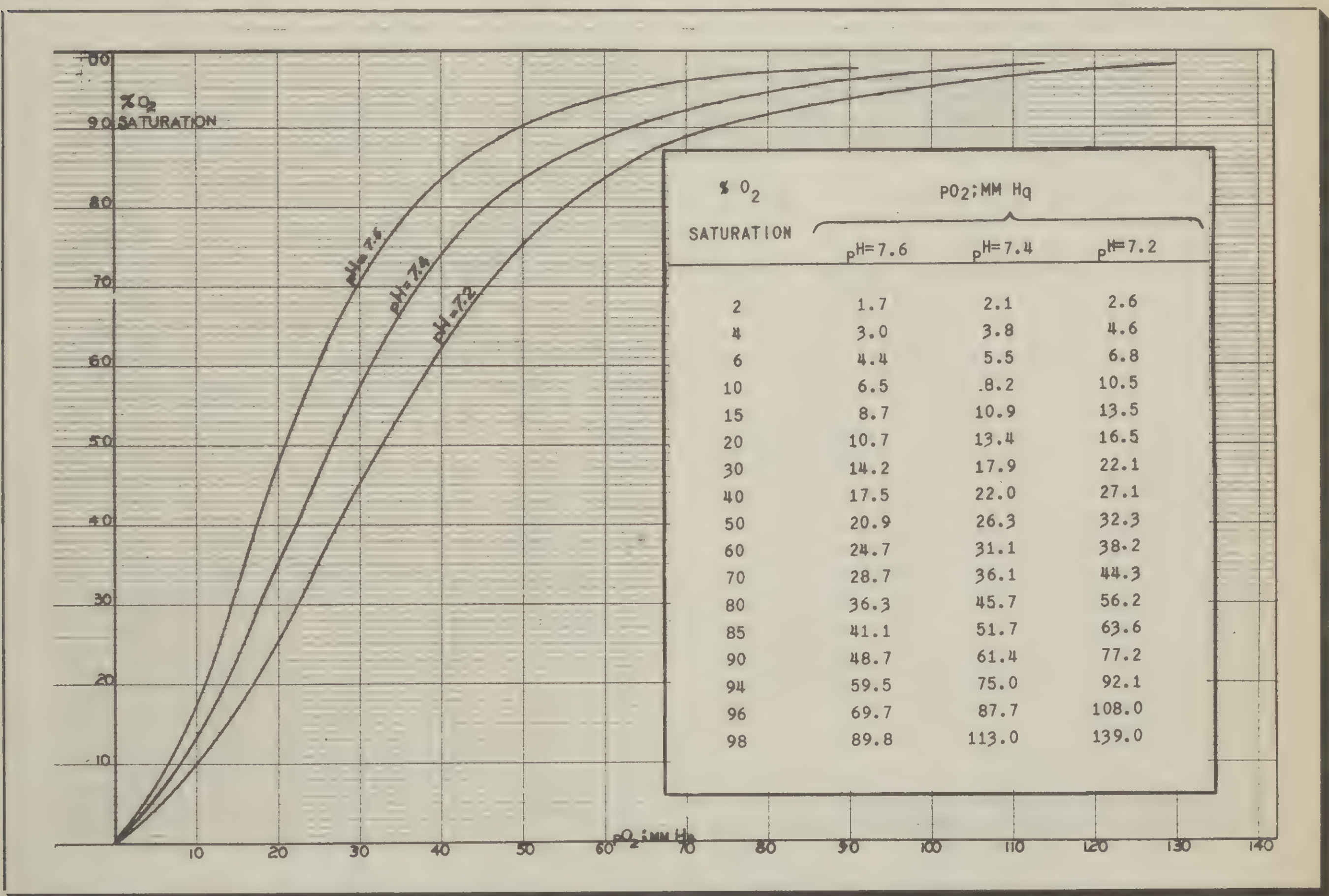
THE TRANSPORT SYSTEM FOR RESPIRATORY GASES.—The transportation of respiratory gases is accomplished mainly by their combination with special constituents of the blood. Far greater quantities of these gases are carried in the blood than could be present in simple solution in the plasma. At sea level pressures, if air is breathed, only about 0.3 cc of oxygen and about 2.5 cc of carbon dioxide are carried in 100 cc of blood in simple solution. Actually, under these conditions, 100 cc of blood contains about 18 to 20 cc of oxygen and about 40 to 50 cc of carbon dioxide. This is about 100 times the amount of oxygen and about 20 times the amount of carbon dioxide that would be carried in simple solution.* The ability of the blood to carry such a large load of oxygen is due to the hemoglobin contained in the red blood cells. Carbon dioxide is carried largely in the form of bicarbonate ions both in the plasma and in the red blood cells.

The Transportation of Oxygen.—Oxygen combines reversibly with hemoglobin in a unique manner to form oxyhemoglobin. In figure 12 curves of dissociation of oxyhemoglobin may be studied and the following facts noted:

1. The combination of hemoglobin with oxygen is influenced by the partial pressure of oxygen in the surrounding medium. This has a direct effect on the ability of blood to transport oxygen to the tissues of the body at various altitudes.

2. Hemoglobin has a relatively high affinity for oxygen at certain partial pressures of oxygen and a rela-

*The amount of oxygen carried in simple solution in the plasma may be increased by breathing higher percentages of oxygen. If 100 percent oxygen is breathed at sea level, 100 cc of blood will carry 2.2 cc of oxygen in simple solution or seven times as much as when air is breathed.



% O_2 SATURATION	PO_2; MM Hg pH=7.6	pH=7.4	pH=7.2
2	1.7	2.1	2.6
4	3.0	3.8	4.6
6	4.4	5.5	6.8
10	6.5	.8.2	10.5
15	8.7	10.9	13.5
20	10.7	13.4	16.5
30	14.2	17.9	22.1
40	17.5	22.0	27.1
50	20.9	26.3	32.3
60	24.7	31.1	38.2
70	28.7	36.1	44.3
80	36.3	45.7	56.2
85	41.1	51.7	63.6
90	48.7	61.4	77.2
94	59.5	75.0	92.1
96	69.7	87.7	108.0
98	89.8	113.0	139.0

Figure 12.—Oxyhemoglobin dissociation curves for human blood.

tively lower affinity for oxygen at lower pressures. The S-shaped curves indicate this phenomenon. Thus, the blood has a high capacity for oxygen at the partial pressure of oxygen in the lungs and a low capacity at the partial pressure in the tissues. This leads to a rapid loading of oxygen in the lungs and a rapid unloading in the tissues.

3. The acidity, conveniently denoted as pH, affects the oxygen-carrying capacity of hemoglobin. (As the pH becomes greater than 7.0, the degree of *alkalinity* is greater; as the pH becomes less than 7.0, the degree of *acidity* is increased.) Variations in acidity are due largely to variations in the content of carbon dioxide, and this, in turn, to respiratory regulation. When one breathes deeply, the partial pressure of carbon dioxide in the blood decreases and the blood becomes more alkaline. The first curve in figure 12 shows that when the pH has increased to 7.6, the blood is 71 percent saturated with oxygen at a partial pressure of oxygen (pO_2) of 30. On the other hand, when respiration is slowed, the blood may become more acid because of the accumulation of carbon dioxide; that is, the pH declines. At this same partial pressure of oxygen of 30 mm Hg, blood at the normal pH value of 7.4 is 58 percent saturated, whereas with a pH of 7.2 it is only 46 percent saturated. Since hemoglobin combined with oxygen is more strongly acid than when it is free from oxygen, it affects the amount of carbon dioxide that can be combined with bases in the blood. Thus, there is a reciprocal relationship between the transportation of oxygen and carbon dioxide. The greater the concentration of oxygen, the less carbon dioxide the blood is capable of transporting. Since carbon dioxide leaves the blood by way of the capillaries in the lungs, arterial blood can carry a larger amount of oxygen than can venous blood. When arterial blood arrives at the tissues where carbon dioxide is produced and transferred to the blood, a relatively greater amount of oxygen must leave the blood for utilization in the tissues. Arterial blood contains, therefore, a relatively larger amount of oxygen, and venous blood a relatively larger amount of carbon dioxide, than would be the case if this reciprocal relationship did not exist. Consequently, hemoglobin plays a very important role in the adjustment of individuals to high altitudes.

Since the combination of oxygen and hemoglobin is a loose one and readily reversible, and since oxygen in the tissues is present by virtue of an efficient process of diffusion, the percentage saturation with oxygen of blood leaving the lungs is a fairly valid criterion of the physiological condition of an individual at various altitudes (figure 10), provided that the circulatory system is functioning properly.

PRESSURE BREATHING.—As has been discussed previously, the oxygen tension of the blood falls below normal (sea level) limits at altitudes above 34,000 feet even though an individual is breathing 100 percent oxygen. When 100 percent oxygen is breathed at 37,000 feet, the concentration of oxygen in the blood is the same as at 5,000 feet when air is breathed. At 40,000 feet, when 100 percent oxygen is breathed, the oxygen concentration in the blood is approximately the same as at 10,000 feet when air is breathed. In order to go above 40,000 feet, some method of delivering oxygen under pressure to the lungs must be used. One method which has been devised is to "pressurize the lungs" by using an oxygen mask which will seal on the face even though a positive pressure is applied. A special regulator, regulator valves, and mask valves are required in addition to the mask for delivering graded amounts of pressure.

Pressure breathing has been used effectively to raise the present practical oxygen ceiling of approximately 40,000 feet. Breathing against pressure entails a reversal in one of the essential characteristics of respiration. Expiration, normally a passive phenomena, becomes an active process. The average normal subject adapts himself rather quickly to this, however, and can breathe for several hours without discomfort against 6 to 8 inches of water pressure while above 40,000 feet. With practice and training, danger from circulatory collapse is negligible, especially when a subject is occupied with a light task such as piloting a plane. Above 8 inches pressure, and especially at 12 inches, pressure breathing can be continued comfortably for only a limited period. In this range, some form of respiratory aid is desirable. At present, two methods are being studied: (1) The use of a pressure vest about the chest and inflated to the same pressure as the lungs. This device is an effective respiratory aid. A modification of this type of pressure vest is a noninflated "zippered" vest which can be adjusted as necessary to restrict chest expansion and thereby produce a similar respiratory effect. (2) The use of "intermittent" pressure breathing, which allows the oxygen pressure to be lowered during the exhalation cycle but maintains a high pressure (12 inches or more) during the inhalation cycle. This method has been used effectively in the chamber up to very high altitudes (52,000 feet).

Ascents to 45,000 feet with subjects breathing against six to eight inches of water pressure are routine during simulated flights in the altitude chamber at the Aero Medical Laboratory. Many successful ascents also have been made to 50,000 feet. In these ascents breathing against 10 to 12 inches of water pressure was employed. While insufficient to allow long periods at 50,000 feet, 10 to 12 inches of water pressure permitted the subjects to remain at that altitude for 15 minutes. While breathing under pressure at 46,000 feet, it is possible to exercise and perform light tasks.

The Circulatory System

RESPONSES OF THE CIRCULATORY SYSTEM TO CHANGES IN ALTITUDE.—Responses of the circulatory system are much more complicated than are those of the respiratory system. Pulse rate and blood pressure do not increase greatly from ground level to 10,000 feet while persons are breathing air, or to 40,000 feet while they are breathing pure oxygen. When an altitude is reached at which the saturation of arterial

blood decreases appreciably, an increase in both pulse rate and blood pressure occurs. This indicates an increased output of blood by the heart.

THE EFFECT OF EXERCISE AT HIGH ALTITUDE.—The compensatory cardiovascular responses to high altitudes and to moderate exercise at sea level are much the same. Thus, whenever exercise is carried out at sufficiently high altitudes so that arterial saturation is below normal, the circulatory stresses which are due to the combined effects of low oxygen and of exercise produce a greater strain upon the individual than would either factor alone.

In acclimatized individuals, mild exercise carried out at a given high altitude may have no greater effect upon pulse rate than it has at sea level, but in nonacclimatized individuals, mild exercise at the same high altitude produces the identical symptoms as does strenuous exercise at low altitudes. Flyers ordinarily do not become acclimatized, because they do not live at high altitudes for a sufficient time for such adjustments to take place. Since physical training accomplishes somewhat similar adjustments in the circulatory system as occur during acclimatization, flyers who engage regularly in some form of physical exercise will better accommodate themselves to high altitudes than will those who lead sedentary lives.

CIRCULATORY FAILURE AND COLLAPSE AT ALTITUDE.—One of the greatest hazards associated with high altitude is the occurrence of peripheral circulatory failure and its concomitants, impaired venous return and decreased volume output of the heart. Injury, loss of blood, severe pain due to aeroembolism, acapnia accompanying hyperventilation caused by apprehension, and anoxia are a few of the causes that may contribute to the occurrence of collapse at altitude. Knisely has found that constriction of the arterioles in the scleral conjunctiva occurs in all individuals at altitudes in excess of 30,000 feet, and that such vasoconstriction is increased prior to the occurrence of symptomatic aeroembolism. Recently digital volume—pulse measurements at the Yale Aero Medical Research Unit have indicated that similar vasoconstriction takes place in the fingers. The intense arteriolar constriction characteristic of collapse at altitude, though a compensary mechanism of value in maintaining blood pressure, leads to capillary anoxia and resultant increased capillary permeability, further loss of effective circulating blood volume, impaired venous return and decreased cardiac output, further tissue anoxia, and hence a vicious circle. It is evident that an abnormally low oxygen saturation of arterial blood in the face of even mild or incipient circulatory failure is extremely perilous.

True collapse at altitude, though not infrequent in decompression chambers, has not yet proved itself a problem in aircraft. This is probably due largely to the longer sojourn at higher altitudes in decompression chambers.

A milder, different form of circulatory failure from that just described occurs at altitudes of around 20,000 feet and is thought to be caused primarily by a combination of anoxia and psychogenic factors. It has been termed "primary shock," simple vasomotor collapse, or neurocirculatory collapse, and involves a mechanism similar to simple syncope on the ground.

Acute and Chronic Effects of Oxygen Want

MEANING OF ANOXIA.—The condition induced by an inadequate concentration of oxygen in the air breathed commonly is known as "anoxia," by derivation meaning "without oxygen," although the common usage of this term implies an intermediate degree of oxygen depletion. The degree of anoxia depends upon the reduction of the partial pressure of oxygen in the alveoli below its normal value. What determines the tactical efficiency of a flyer at high altitudes is the amount of oxygen which is available to the cells of his body, particularly to those comprising the central nervous system.

FAILURE OF CELLS TO CARRY ON THEIR NORMAL PROCESSES OF ENERGY EXCHANGE.—Interference with the normal supply of oxygen to the cells of the body affects the manner in which they carry out the normal processes of producing energy. The amount of oxygen supplied to the cells may depend on any one of three conditions, or a combination of them.

1. The first and most common condition encountered is a low amount of oxygen in the air breathed, a type of anoxia encountered at high altitudes when the flyer neglects to use his oxygen equipment or when it fails.

2. A second condition also confronted by flyers is inability of the blood to transport enough oxygen, either because of anemia resulting from excessive loss of blood or because of carbon monoxide poisoning. In the latter condition, the oxygen-carrying red blood corpuscles temporarily have a lessened capacity for oxygen. Unfortunately, the hemoglobin of the red blood cells has about 200 times greater affinity for carbon monoxide than for oxygen. As a result, even in low concentrations of carbon monoxide, hemoglobin combines with this gas to the partial exclusion of oxygen.

3. The quantity of oxygen delivered by the blood to the cells depends not only on the oxygen-combining capacity of the blood but also on the rate of flow of the blood. This normally is increased in a healthy person exposed to oxygen deficiency, but it may be decreased as a result of fear, pain, or injury, particularly if the injury involves loss of blood.

4. The ability of tissue to utilize oxygen may be impaired by poisons which interfere with cellular respiration. Alcohol and cyanide are two of the agents which produce this effect.

PHYSIOLOGICAL STATES INDUCED BY ANOXIA.—Under ordinary conditions at ground level, the blood is approximately 95 percent saturated with oxygen. An increased rate of breathing or the breathing of pure oxygen increases the saturation; in the latter case it raises it to approximately 100 percent. This small increase of the oxygen in the blood has but little physiological effect

in a healthy person. On the other hand, if saturation decreases to much less than 95 percent, untoward reactions become evident.

The relationship of altitude to the oxygen saturation of arterial blood, subsequently referred to as "arterial saturation," is evident in figure 10, in which the expected arterial saturation at a given altitude, together with a statement of expected symptoms, is shown. It is clearly depicted that 19,000 to 20,000 feet, with the individual breathing air, and about 44,800 feet, with the individual breathing oxygen, are the highest tolerable altitudes for exposures lasting longer than a very few minutes. Length of exposure is a very important consideration. Most men can tolerate an altitude of 18,000 feet for a half-hour without using oxygen, but even though they may be conscious they will be in a befogged state, and collapse almost certainly will ensue. It is possible to remain conscious for a few minutes at 25,000 feet, but at such an altitude collapse occurs more rapidly. Consciousness may be lost within a minute at 30,000 feet and within 30 seconds at 35,000 feet. At 25,000 feet, death soon follows loss of consciousness. According to Eighth Air Force reports, it may occur after only five minutes of unconsciousness at 25,000 feet.

Lowering of the arterial saturation from 95 to 85 percent, if it happens slowly, may not affect the ability of a flyer to do his job. He may himself be unaware of any change until he starts working, as, for example, operating a flexible machine gun, when he will experience shortness of breath. This range of anoxia, extending to as low as 85 percent arterial saturation, can be tolerated for considerable periods (figure 10), but results of psychological tests show that reduced performance in mental tests occurs and that the carrying out of complicated operations comparable to blind flying is impaired. Frequent errors in judgment may be made. Navigational problems may become increasingly difficult to solve, jeopardizing the mission or even the lives of the entire crew.

Whereas an arterial saturation of 85 percent may have only slight effect in daytime flying, it is very serious at night because of the effect on night vision. Even the slightest degree of anoxia greatly reduces the ability to see at night, and it is for this reason that all flyers are ordered to use oxygen at any altitude, from the ground up, on all combat and tactical missions at night.

Further lowering of the arterial saturation to about 80 percent produces greater effects (figure 10), even on a resting person, particularly if the period of exposure is long. Vision is somewhat dimmed even in daylight; at night it is affected considerably. Tremor of the hands may appear or increase, errors in judgment are frequent, and thinking and memory are clouded. Respiration usually begins to increase. Collapse at this degree of saturation is rare, except in cases of pain or fear, when fainting may result. Exercise, with this degree of anoxia, becomes increasingly difficult, and the onset of fatigue is rapid. Breathlessness and panting result from exercise.

A saturation of 75 percent approaches the danger zone; the handicap is great. Even while a person is resting, respiration increases. Exercise causes deep breathing and the muscles doing the work feel "leaden." Pain in the muscles which are being used may force the subject to stop working. Symptoms like those previously described are present, but to a greater degree. Fainting is frequent when pain or fear complicates the situation. Although some people lose much of their reasoning power, not everyone is so seriously affected, and a considerable degree of mental ability may be retained for periods of moderate length. A resolute pilot may marshal reserves of will power and fly his plane successfully for some minutes.

An arterial saturation of 70 percent approaches the limit of human tolerance (figure 10). At such a saturation a wide variation is noted in the responses of different persons. If the exposure is not too long, many people can perform moderately difficult tasks, and mental capacity is not critically impaired. However, breakdown is very frequent, and again, pain or fear may cause the person to collapse.

Arterial saturations ranging as low as 60 percent may allow many subjects to remain conscious if the lowering of the saturation has been rapid and if it is not prolonged. Figure 10 shows the expected arterial saturation of oxygen at 44,800 feet. Eight experienced subjects have spent from 15 to 44 minutes at this simulated altitude in the low-pressure chamber, and arterial punctures have been performed; the result of the analyses of the blood forms the points noted in figure 10 for the altitudes shown. Only one of eight subjects who took part in these tests was near collapse at any time during the experiments. The subject whose arterial saturation was 62 percent was able to perform arterial puncture on another subject after having had his own blood drawn. With excitable or inexperienced subjects it is doubtful that this could have been done.

When the arterial saturation decreases to about 60 percent, coordination is lost. This stage represents a brief transitory period between useful consciousness and total collapse.

Recovery from Anoxia.—Recovery from anoxia is rapid when sufficient oxygen is supplied. An individual on the threshold of unconsciousness may regain his full faculties within 15 seconds when an abundance of oxygen is furnished him. Some have the impression that a person in such a state should resume the use of oxygen cautiously. There is no convincing evidence supporting such an idea. Experience shows that if a person who is very anoxic breathes deeply of oxygen he may occasionally experience a flash of dizziness, but this passes immediately, and complete restoration of normal function follows. Permanent brain damage resulting from anoxia has been comparatively rare. There have been few such authenticated cases.

Headache.—Headache is a common complaint of persons after a prolonged period of severe anoxia. Some people appear to be very susceptible to this type of headache. It appears to be general, but is particularly acute in the frontal region. The best cure is sleep, although when it is severe, the administration of 100

percent oxygen is advisable. The headache has been explained as the result of edema or "water-logging" of the tissues, particularly the nervous tissues, as a consequence of an increased permeability of the capillaries caused by the anoxia.

Ceiling.—Individual variation in the ability to withstand anoxia is considerable; it accounts for variation in "ceiling." This may be related to a person's respiratory adjustment; that is, to the stimulation his respiratory center receives as a result of anoxia. Although any healthy flyer breathes more deeply when he becomes very anoxic, his breathing may be, at a given altitude, increased from 50 percent to 200 percent. In tests performed at a simulated altitude of 44,800 feet in the low-pressure chamber, the only man who complained of a subsequent headache had experienced the least increase in breathing.

Increased Breathing in Anoxia.—The immediate gain resulting from the deeper breathing that occurs involuntarily in acute exposure to oxygen deficiency is twofold. Extra carbon dioxide is removed, increasing the oxygen in the lungs and making the blood more alkaline, thus favoring the uptake of oxygen by the hemoglobin of the blood. At such extreme altitudes as 40,000 feet, where pure oxygen must be breathed, the barometric pressure, which is the same in the lungs as it is outside, equals the sum of the partial pressures exerted by water vapor, carbon dioxide, and oxygen. The pressure of the water vapor is relatively constant, tending to correspond to a saturated state at 37° C. Consequently, lowering of the partial pressure of carbon dioxide, such as occurs in deep breathing, will increase the partial pressure of oxygen in the lungs by an approximately equivalent amount.

Apprehension.—It is well known that inexperienced personnel collapse more frequently at intermediate altitudes, when the arterial oxygen saturation is still not greatly reduced, than do experienced individuals. The factors involved in such collapse are primarily psychogenic and are due to apprehension. The overventilation produced by anoxia ordinarily lowers alveolar carbon dioxide enough to produce minor symptoms, like dizziness, but does not have more serious effects. However, an individual who is apprehensive may hyperventilate to a greater extent, thus further reducing an already decreased carbon dioxide tension and producing a degree of acapnia associated with more marked symptoms, like tingling of the fingers and toes, blurring of vision, and carpopedal spasm. Such acapnia, added to the splanchnic vasodilatation which is a not infrequent response to fear, may bring about neurocirculatory collapse. It must be stressed that overventilation confined to that occurring in response to the stimulation of the carotid chemoreceptors by anoxia does not produce serious acapnia. The "hazards" of deep breathing are confined to cases of marked hyperventilation arising out of apprehension. Education and experience tend to combat this.

The Relationship of Shock to Anoxia.—Shock is a circulatory deficiency characterized by decreased blood volume, impaired venous return, decreased cardiac output (reduced volume flow), and increased concentration of the blood. In shock more than the usual number of capillaries are open and filled with blood; it has been appropriately said that in shock a man bleeds into his capillaries. Pooling of the blood results, particularly in the abdomen (splanchnic area). The causes of this vasomotor collapse are varied, including such things as fear, pain, and loss of blood. In the presence of any of these potential causes, anoxia may be the precipitating factor in the occurrence of shock. When present in shock which is due to other causes, it is always a contributing factor, and it may facilitate the establishment of a vicious cycle of events leading to general collapse. Anoxia itself, even in its early stages, may produce vasomotor collapse in some individuals.

The Supply of Oxygen to the Brain and Central Nervous System.—The amount of oxygen supplied to the brain and central nervous system is dependent upon both adequate circulation of blood to the brain and the concentration of oxygen in the blood. If the content of oxygen in the blood supplied to the brain is normal but the flow of blood is decreased, the oxygen supply to that organ will be diminished, causing fainting at ground level. When the flyer's equipment fails to supply him with the proper amount of oxygen at altitude, his brain is the first organ to suffer. Superimposed on this condition, a circulatory handicap arising from fear, pain, or loss of blood may produce collapse when either state in itself could have been withstood.

Chronic Anoxia.—The reactions mentioned thus far in this section pertain to a subject who is anoxic for only a short time, that is, a matter of a few hours at the most. The person who remains for days, weeks, or months in a state of oxygen deprivation has very different experiences. Such a person undergoes certain organic, largely chemical, changes, the whole process of which is termed "acclimatization." This occurs in persons who go to mountain communities to reside for some time. Headache, nausea, and weakness often accompany the process of acclimatization. Men have become acclimatized to altitudes as high as 17,500 feet. In Chile there is one community of about 100 sulfur miners and their families who live at this altitude.

Tragedy at High Altitude

The following two reports from The Air Surgeon concern subjects who passed through the stages of anoxia which have been described in this chapter. The stories are presented to stress the treacherous effects of lack of oxygen.

> The pilot gunned the motors and the B-17 roared down the runway of an Army airdrome in the western United States, eased into the air, and soared away on a routine practice bombing mission. On board were the pilot, copilot, two cadet bombardiers, and an engineer-aerial gunner. Four hours later the same B-17 made an emergency landing at a naval air base.
>
> When a medical officer opened the waist door, he found the engineer dead, bombardier A dying, the pilot suffering from acute oxygen starvation, and the copilot and bombardier B conscious but dazed. Bombardier A died a few minutes after the

landing, and only the copilot, who, apparently, was the only one who at no time during the mission had lost consciousness, could walk off the field.

The stories of the three survivors, obscure as to detail, disjointed, sometimes conflicting, give testimony to the tricks that oxygen starvation, or anoxia, can play on the human mind. But woven together they give this picture of what happened during the tragic flight:

The first part of the mission had been uneventful and, after leaving the bombing range, the pilot started to ascend for the next phase of the mission—high altitude instrument flying.

They climbed into some overcast and crew members were ordered onto oxygen at 12,000 feet; the pilot leveled off to permit them to put on their oxygen masks. Both the pilot and copilot said they had difficulty fitting their face pieces and finally tried to prevent leakage by holding the mask to the face with one hand. They both used the A-10 mask.

The pilot resumed his climb, but somewhere between 20,000 and 24,000 feet, the ship stalled and the pilot fainted, falling out of his seat. The copilot felt himself fall toward the roof of the cabin, lost his oxygen mask and headset, but worked frantically to bring the ship out of the spin. Then the pilot began to regain consciousness, and finally both succeeded in restoring their masks and getting the ship under control.

The engineer also had lost his mask during the erratic plunge of the ship. After the plane was under control again, however, the pilot could see the engineer in the radio compartment with his mask apparently readjusted. Then the pilot took the ship up to 31,000 feet to try to recover the radio signals which had been lost during the first ascent. After finding the radio beam, he began his descent homeward.

At this point he gave the controls to the copilot and personally checked his crew. He could see the interior of the ship, he said later, and got an OK from the engineer. He also looked into the bombardier's compartment and got an OK signal from bombardier A.

When the pilot resumed control of the ship, he noticed no manifold pressure on engine No. 1, so began a let-down and came out of the overcast near the naval base at about 5,000 feet. It was then that the copilot went back to check the crew. He found the engineer unconscious in the radio compartment, his oxygen mask beside him. After trying to give oxygen to the unconscious man, the copilot reported to the pilot, who told him to get help from one of the bombardiers. But in the bombardier's compartment, the copilot found that bombardier A was unconscious, with his mask off. Bombardier B, although using the portable oxygen bottle, was so weak he could not help.

Again the copilot reported to the pilot, who radioed the naval base that he was coming down and requested emergency medical treatment for his crew. The pilot made a perfect landing, although afterward he could not recall lowering either the wheels or the flaps.

Bombardier B said nothing unusual had happened until the ship had begun to fly erratically. Then the cushions and papers seemed to move around the ship and the pitching movement threw bombardier A from his seat. Bombardier B recalled trying to adjust the other's mask, and, as things began going dim, trying to keep him from jumping through the emergency hatch. This would have been about the time the pilot said he had received an OK signal from bombardier A, evidence of the confusion which anoxia will produce in a man's mind. Bombardier B could remember nothing else that had happened until the copilot asked him to help just before landing.

The medical staff found that the engineer and bombardier A had both died of severe anoxia. An examination showed that the plane's oxygen system, the demand type, was apparently in perfect working condition, but the oxygen masks had not been properly fitted and adjusted.

This is only one example of the deadly cost of carelessness in the use of oxygen equipment.

Some time ago a B-17 landed at an Army air field in Florida with one of the crew dead of anoxia. Before taking off, the pilot had carefully instructed his crew of four—a copilot, crew chief, sergeant, and private—in the use of the demand-type oxygen system. The private was seated in the radio compartment while the sergeant climbed into the ball turret to test its operation.

The total flight time was not more than 45 minutes, of which not more than 15 were spent above 20,000 feet and less than 30 seconds at the maximum altitude of 28,000 feet. When the sergeant crawled out of the turret at 10,000 feet on the homeward descent, he found the private lying dead on the floor. His mask had been disconnected from the regulator hose which he had hung carefully by its clamp on the seat ahead of him. His own portable unit stood in the rack beside his seat, unused. For some reason he had decided to leave his station, neglected to switch over to the portable unit, and collapsed.

Accidents like this can be avoided only if everyone, from the individual crew member up to the unit commanding officer, realizes that oxygen equipment is the barrier that stands between a man and death at high altitudes. If oxygen equipment is used properly, high altitude operations are no more hazardous than low level operations, but the equipment is only as efficient as the man who uses it.

CHAPTER III
ARMY AIR FORCES OXYGEN EQUIPMENT

The physiology of respiration and the flyer's need for supplementary oxygen at high altitude has been discussed in chapter II. Once the actual amount of oxygen required at various altitudes to maintain satisfactory oxygen saturation in arterial blood is known, the delivery of oxygen according to these requirements becomes an engineering problem. This problem with its various phases is the subject of this chapter.*

Though complex in detail, air-borne oxygen systems generally consist of 5 main parts:

1. The oxygen supply.
2. Means of reducing oxygen pressure from that at which it is stored down to a pressure suitable for breathing.
3. Means of controlling the rate of oxygen flow.
4. Instruments for indicating whether oxygen is flowing and how much oxygen remains in the supply.
5. Masks designed to fit properly and to function at high altitude.

Requirements for Oxygen Systems

Oxygen equipment of any type must meet certain requirements. These may be grouped as physiological and physical.

Physiological Requirements.—All equipment must be manufactured to conform as nearly as possible to the specifications imposed by the following physiological requirements:

Concentration of Oxygen Delivered.—The need for increasing amounts of oxygen has already been discussed. The equation for determining the required amount is

$$FO_2 = \frac{pO_2 + pCO_2}{P_B - 47 - pCO_2 + \frac{pCO_2}{R.Q.}}$$

when FO_2 = fraction of oxygen required
pO_2 = partial pressure of oxygen desired
pCO_2 = partial pressure of CO_2 in expired air
P_B = pressure at altitude
R.Q. = respiratory quotient
47 = partial pressure of water vapor

A simplified equation for calculating tracheal air is more easily used

$$FO_2 = \frac{pO_2}{P_B - 47}$$

*This discussion presumes some familiarization with AAF oxygen equipment described in T. O. 03-50-1 dated 1 July 1944, "Use of Oxygen and Oxygen Equipment" and subsequent revisions thereof.

The percentage of oxygen required to simulate different altitudes is shown in figure 13.

Ventilation Volume and Ventilation Rates.—The average inspired volume of gas of flying personnel is assumed to be 14.2 liters per minute at body temperature, ambient pressure, saturated with water vapor at 37°C (12.6 L STPD). Actual experimental tests have recorded ventilations as high as 60 liters per minute. These figures indicate only the volume of gas taken into the lungs and give no indication of the instantaneous rates of flow of gas into the lungs. It has been determined experimentally that the highest instantaneous rate of flow during one respiration can be estimated by multiplying the ventilation by three. A significant portion of the tidal volume is also taken in at relatively low rates of flow. Both of these factors must be taken into account in the design of oxygen equipment. Reference should be made to chapter II for a more detailed discussion of respiratory ventilation.

Respiratory resistance.—A third factor that must be considered is the resistance encountered in inspiration and expiration. Tolerable resistances have been determined and are shown in figure 14.

Physical requirements.—Oxygen equipment must conform to the following standards:

1. Least possible weight of cylinders, fittings, and instruments.
2. Rugged construction; performance for 500 hours of flight.
3. Cylinders which do not shatter or explode when hit by bullets or flak.
4. Easily maintained and serviced components.
5. Proper functioning at temperatures between —65 and 160° F.
6. Material which does not mold, mildew, or deteriorate under adverse climatic conditions.
7. Adaptability for manufacture in large quantities.

Oxygen Storage Systems

LIQUID OXYGEN.—The first method of storing oxygen in the Air Corps was as liquid oxygen, in general use from 1920 to 1936, when it was replaced by gas storage cylinders. Liquid oxygen has the advantage of occupying a small space and requiring less weight for a given quantity of oxygen. These advantages at present are greatly overweighed by several disadvantages. Liquid oxygen vaporizes continuously and therefore cannot be stored for indefinite periods of time. Transport of liquid oxygen for servicing aircraft would constitute a drawback to the AAF under present operating conditions.

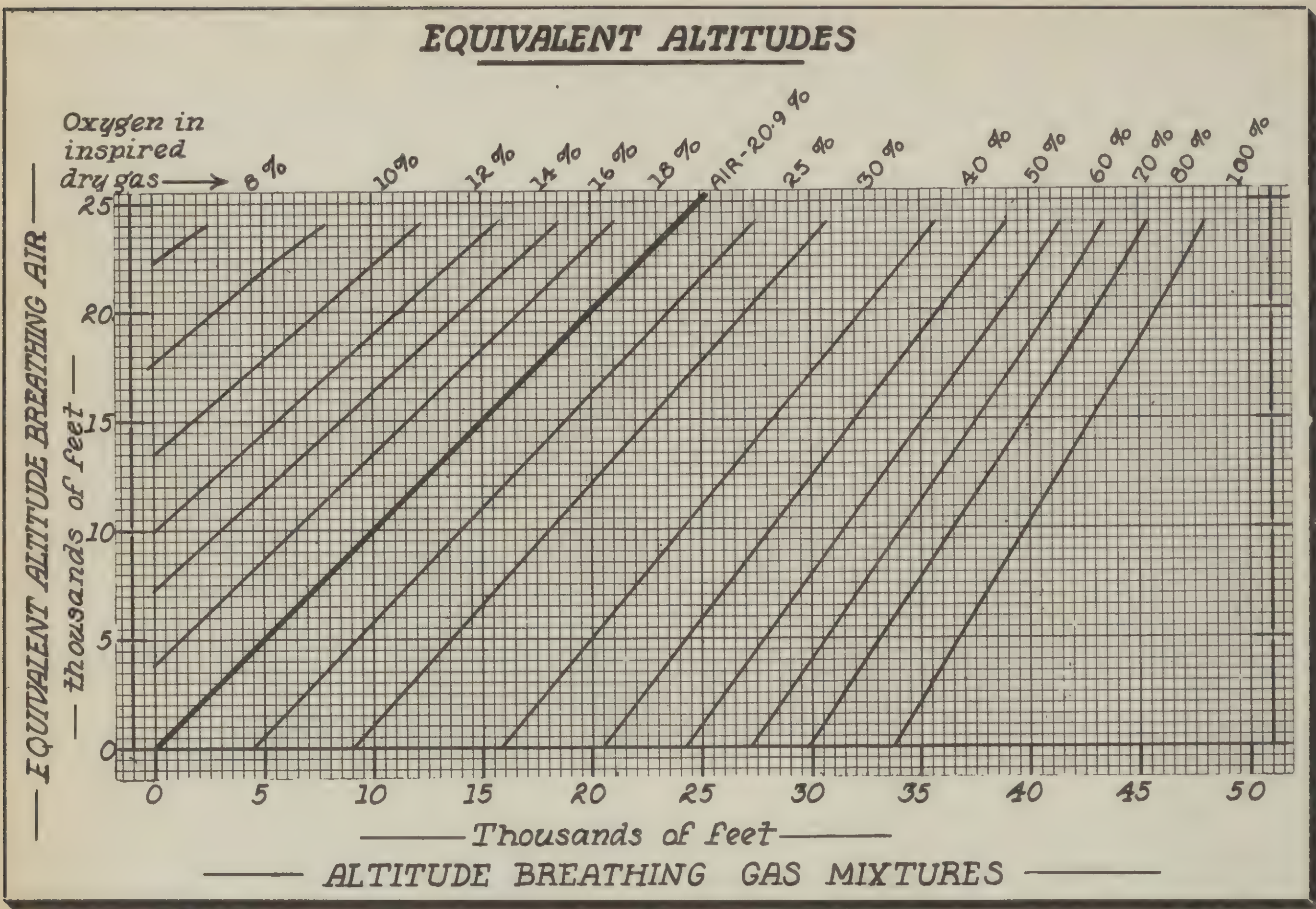


Figure 13.—Equivalent altitudes breathing gas mixtures. Figure shows relation between physiologically equivalent altitudes for persons breathing gas mixtures containing various concentrations of oxygen. Equivalent altitudes are defined in terms of identity of alveolar gas composition; the values shown are valid only under these defined conditions. If, as a result of pain, fear, or other factors, an individual hyperventilates in such a way that the alveolar carbon dioxide tension varies independently of the alveolar oxygen tension, the values in the figure do not apply. (From Handbook of Respiratory Data in Aviation, Committee on Aviation Medicine, National Research Council.)

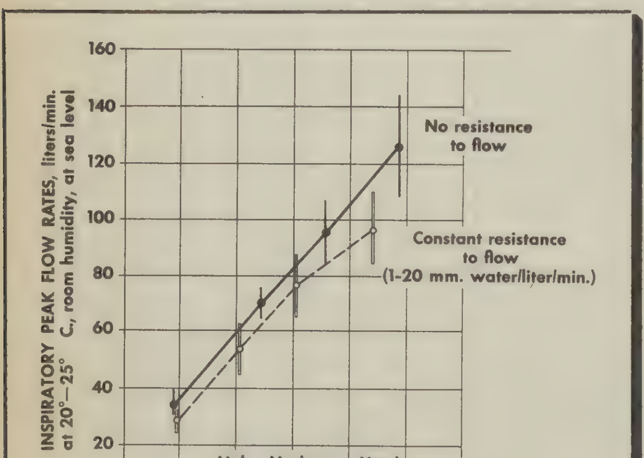


Figure 14.—Peak inspiratory velocities during exercise at sea level with varying inspiratory resistances. Vertical lines indicate standard deviation about the mean. Solid circles show mean values from subjects breathing with inspiratory resistance to flow. Open circles give mean values from the same subjects breathing against a constant inspiratory resistance of 1.20 mm H_2O per liter/min. This resistance is enough to cause discomfort even at flow-rates as low as 10 liters per minute. Results obtained from lesser values of resistance are included between the extremes shown in the figure. B.T.P.S. refers to recalculation of respiratory minute volumes from the original data to body temperature and pressure, saturated. (From Handbook of Respiratory Data, Committee on Aviation Medicine, National Research Council—after Harvard Report OSRD No. 1222.)

Furthermore, storage vessels have not proved safe against gunfire. The study of liquid oxygen has been revived recently by the AAF and the Navy, in an attempt to make use of the small volume and weight characteristics of liquid oxygen systems in modern long range aircraft which may carry many passengers. In such aircraft the space and weight required for large amounts of oxygen become critical, especially if oxygen is stored at low pressure.

The AAF originally changed from liquid to high pressure oxygen storage cylinders with an operating pressure of 1,800 to 2,000 psi. *(See figure 15.)* In 1942 the AAF, after careful consideration, changed to low-pressure (400 psi) storage cylinders. *(See figure 16.)*

High-Pressure Versus Low-Pressure Cylinders

Servicing of High-Pressure Cylinders.—The very first difficulty encountered is in the servicing or recharging of the high-pressure cylinders. The usual practice is to install these cylinders in the airplanes so that they are removable for filling. These cylinders, when nearly empty, are removed from the airplane and replaced with a full cylinder. The near-empty cylinder is then taken to a filling place, where it is charged with oxygen to a pressure of 1,800 psi directly from commercial-type 220-cubic foot oxygen storage cylinders. Inasmuch as these commercial-type cylinders are charged only to pressures of about 1,800 to 2,000 psi, the filling process is not a simple matter.

The common method used in filling is the cascade type. In this process, several commercial-type storage cylinders are used, the pressures of which may be any-

Figure 15.—High-pressure oxygen cylinders.

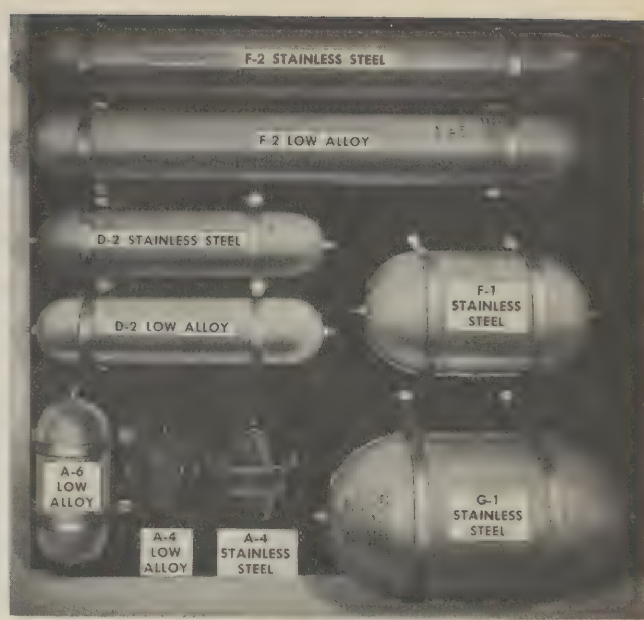


Figure 16.—Low-pressure oxygen cylinders.

where from 500 to 2,000 psi. The aircraft cylinder is recharged from the several storage cylinders by starting the charge from the cylinder with the lowest pressure and then using the other cylinders successively. In this manner, by successively equalizing pressures, the aircraft cylinder is brought up to full pressure when the final 2,000 psi storage cylinder is used. Due to the heat of compression, the aircraft cylinders must be placed in a bath of cold water to insure that a normal charge of 1,800 psi is obtained. These cylinders are then returned to the flying line, where they will be ready for use. Another method of filling high-pressure aircraft cylinders is by use of an oxygen compressor. This method is more efficient, in that it expedites the filling operation and does not require a fully charged storage cylinder to provide the necessary normal charge of 1,800 psi. These methods of filling cylinders are not only tedious, but also entail a waste of time in moving the aircraft cylinders from the flying line to the filling station and then back to the flying line.

To simplify the filling procedure, high-pressure cylinders can be permanently installed in the airplane and manifolded so that they can be filled from an oxygen conveying cart through a common filler valve in the airplane. The cascade method of filling is used or the cart may be equipped with an oxygen compressor. Because of the heat of compression, the cylinders must be overcharged to insure a full charge after they cool down. If they are not overcharged, an extra charge is necessary, after cooling, to achieve full pressure.

This servicing of the high-pressure system requires heavy and complicated units, special high-pressure regulators, gages, valves, and bases, and a prime mover to move the cart about. Suitable light and high-capacity compressors that would make the recharging more efficient are not yet available. The complete high-pressure servicing carts are expensive and limited in production

rate. Many of these units are required to properly meet the needs of a combat base.

Gunfire and High-Pressure Cylinders.—A second disadvantage of high-pressure oxygen cylinders is their behavior under gunfire. When any high-pressure cylinder charged with oxygen is punctured by a .30-caliber bullet, the steel around the entrance hole burns in the oxygen atmosphere, producing an extremely hot, long flame of short duration. This flame certainly constitutes a hazard. When the old-type, non-reinforced, high-pressure oxygen cylinder is struck with a .50-caliber bullet, the cylinder explodes or shatters into several parts with great violence and is capable of completely disabling an airplane. A cylinder of this type was placed in the tail of an old pursuit airplane and was hit with a .50-caliber bullet. The resulting explosion took off the entire tail of the airplane.

It was, therefore, found necessary to reinforce these cylinders properly. A method has been devised to prevent the high-pressure cylinder from exploding, although not from burning, by winding two layers of high-tensile piano wire around the cylinder. After the problem of explosion was solved, a bracket was designed to hold the cylinder and prevent it from "rocketing" when shot. Although the bracket will hold the cylinder, the structure of the airplane must be reinforced so that the bracket will not tear away from its mount. Even though it is properly mounted, the blast from the cylinder when it is shot may tear open the "skin" of the airplane. Gunfire tests conducted on high-pressure cylinders mounted in airplanes have proved that fires may be readily started in this way. The blast of flame resulting from a high-pressure cylinder that has been struck may cause not only adjacent upholstery and wiring to burn, but even, as actually occurred, upholstery and wiring 6 feet away. If unchecked and allowed to get out of control, the fire may consume the entire plane.

Servicing of Low-Pressure Cylinders.—Low-pressure oxygen cylinders were first developed because they could be charged from commercial-type storage cylinders with pressures as low as 500 psi. The servicing equipment used is light, simple, inexpensive, available in large quantities, and is easily handled on the flying line.

Gunfire and Low-Pressure Cylinders.—The second reason for the development of low-pressure cylinders arose from the results of gunfire tests. The old-type low-pressure cylinders, when pierced by .30-caliber and .50-caliber bullets, proved to be superior to the high-pressure cylinders in that they did not shatter and showed no visible flame of fire, no burning of the metal around the bullet holes in the cylinder, and little tendency to rocket. These cylinders required only a couple of straps to hold them in the airplane, and needed little or no reinforcing of the airplane structure at points at which the cylinders were mounted. Low-pressure cylinders thus satisfactorily withstand gunfire without shattering, do not result in fires in the airplane, and do not require any elaborate or extra heavy structure for support.

Oxygen Dispensing Equipment

When a liquid source of supply was used the oxygen was dispensed to the flyer at the rate of vaporization from the liquid. Use of high-pressure cylinders necessitated a regulating device. The simplest of these is a continuous flow model. A regulator of this type was employed during World War I when British high-pressure storage cylinders were in use. The A-6 regulator was the first Air Corps production model and it was used with an A-7 mask or with a pipestem which had been employed with practically all oxygen systems previous to that time.

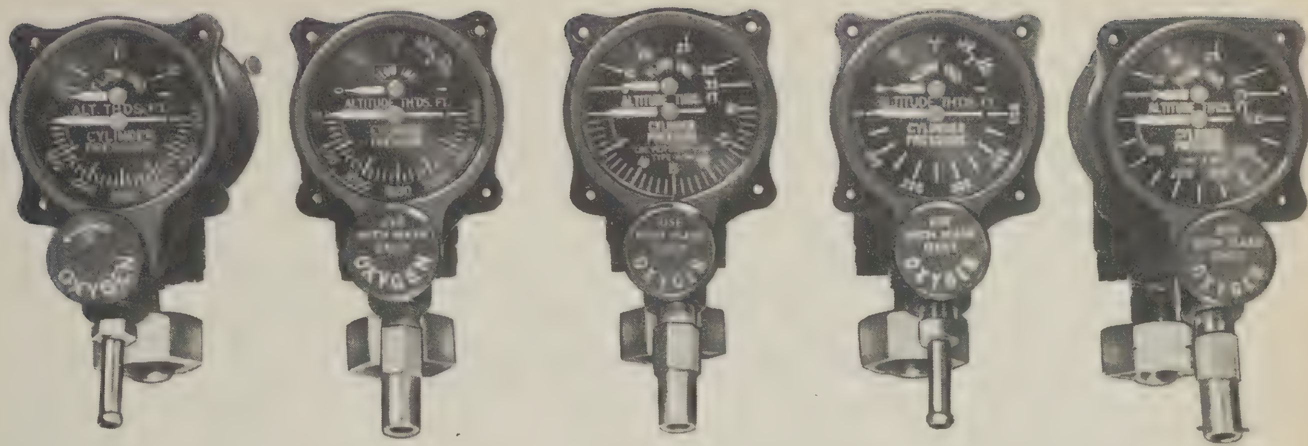
PIPESTEM.—The pipestem was nothing more than a rubber tube held in the mouth between the teeth. This method of administering oxygen was extremely unsatisfactory. When this system was used, oxygen poured continually into the flyer's mouth, puffing up the cheeks and requiring that the mouth be held open, to allow excess oxygen to escape. Some pilots would "bite off" the oxygen. This consisted essentially of closing the teeth on the pipestem at the end of every inhalation and thus stopping the flow of oxygen during exhalation. However, this procedure was detrimental to the oxygen regulator.

In the event that the oxygen was cold, as it frequently was, the sensation caused by the oxygen pouring into the mouth out of the pipestem was very much akin to that of holding an icicle in the mouth. The use of the pipestem necessitated breathing by mouth. To breathe through the nose could be fatal at altitudes above 30,000 feet. Mouth breathing, of course, is undesirable, inasmuch as the normal method of breathing is through the nose or through both the nose and the mouth.

Above all, the pipestem method of administering oxygen was extremely inefficient. A large amount of oxygen was wasted, for the body simply did not use it. With the subject at rest, that part of the respiratory cycle during which air is being drawn into the lungs occupies less than one-half the total time required to complete the cycle. In the continuous-flow system without reservoir bag an individual under the most favorable conditions would inspire only from 40 to 46 percent of the oxygen flowing from the regulator. These percentages are those delivered during the inspiratory phase and the pause immediately preceding inspiration.

OXYGEN MASKS.—The first type of oxygen mask, the type A-7, was constructed with a dipped rubber nasal cover, containing two dependent rubber tubes around the wearer's mouth, terminating in a single supply tube below the chin. One of the greatest disadvantages of this mask was the danger of breathing through the mouth. It soon became obsolete for use in combat.

The A-8 oxygen mask then was adopted. This mask was an oronasal type, operating on the same principle as the A-7. The mask had a simple sponge rubber disc in a turret on the front of the face piece which functioned as an air-mixing valve. The A-6 regulator was modified to give the substantially lower flows that could be used with the rebreather bag system and was desig-



A-6 A-8 A-8-a A-9 A-9-a

Figure 17.—Continuous-flow oxygen regulators. Reading from left to right, the regulators illustrated are the A-6, A-8, A-8A, A-9, and A-9A.

nated type A-8. This regulator later was changed to give increased flows that were found to be necessary when moderate work was being done and designated the type A-8A. The A-9 and A-9A regulators are the counterparts of the A-8 and A-8A which operate on the low-pressure (400 psi) storage system. The A-6, the A-8, and the A-9 series of regulators are shown in figure 17.

At present an improvement of the A-8 mask known as the A-8B is standard. *(See figure 18.)* An improvement of the original A-7, known as the A-7A, is also standard for use in cargo aircraft below 20,000 feet. *(See figure 19.)*

CONTINUOUS FLOW OXYGEN SYSTEM.—Physiological requirements are met, with one exception, by

Figure 18.—A-8B oxygen mask.

Figure 19.—A-7A oxygen mask.

the continuous-flow system, using the rebreather reservoir-type mask. The exception results from the fact that the flow is fixed at any given altitude. If the flow is adequate to provide a partial pressure of oxygen to simulate ground level conditions at a ventilation rate of 15 liters per minute, the partial pressure of oxygen will be lowered, and the simulated altitude will be raised correspondingly by doubling the ventilation.

Physical requirements are generally well satisfied by the continuous flow system but again a serious exception exists. The process of collecting expired air and that of drawing ambient air through the sponges and expiring saturated warm air in the reverse direction leads to serious complications. Freezing occurs in the rebreather bag, the joining yoke, and in the sponges. This may be relieved in part by a hood and completely eliminated by the application of electrical heat.

In passenger aircraft the physical requirements are less rigorous than in combat aircraft because of the lower ceiling. Here an automatic continuous-flow system, as provided by the A-11 regulator, is in use for passengers. Development is proceeding on continuous-flow systems for cargo aircraft, since they offer the promise of further simplicity and comfort, both of which are important to crews who may be at altitudes requiring oxygen for 12 or more hours.

DEMAND OXYGEN SYSTEM.—The demand-type oxygen system most adequately meets all requirements for oxygen equipment in high-altitude combat aircraft. It provides sufficient oxygen automatically for all lung ventilations encountered and the masks used are less affected by cold temperatures than are those of the continuous flow system.

Production designs of demand regulators are used which operate on different principles, but the oxygen is delivered in the same manner. The two designs of diluter demand regulators, shown schematically in figures 20 and 21, have been procured by the AAF, since both meet specified requirements. Outward appearances differ, as shown in figures 22, 23a and b. The original A-12 regulators have been restandardized in the type known as AN 6004-1.

In the development of demand oxygen systems, the importance of the amount of suction in the regulator, required to produce an adequate flow of gas, and, to a greater extent, the importance of a "leak-tight" demand oxygen mask have been stressed. Since intake of oxygen is accompanied by a negative pressure in the

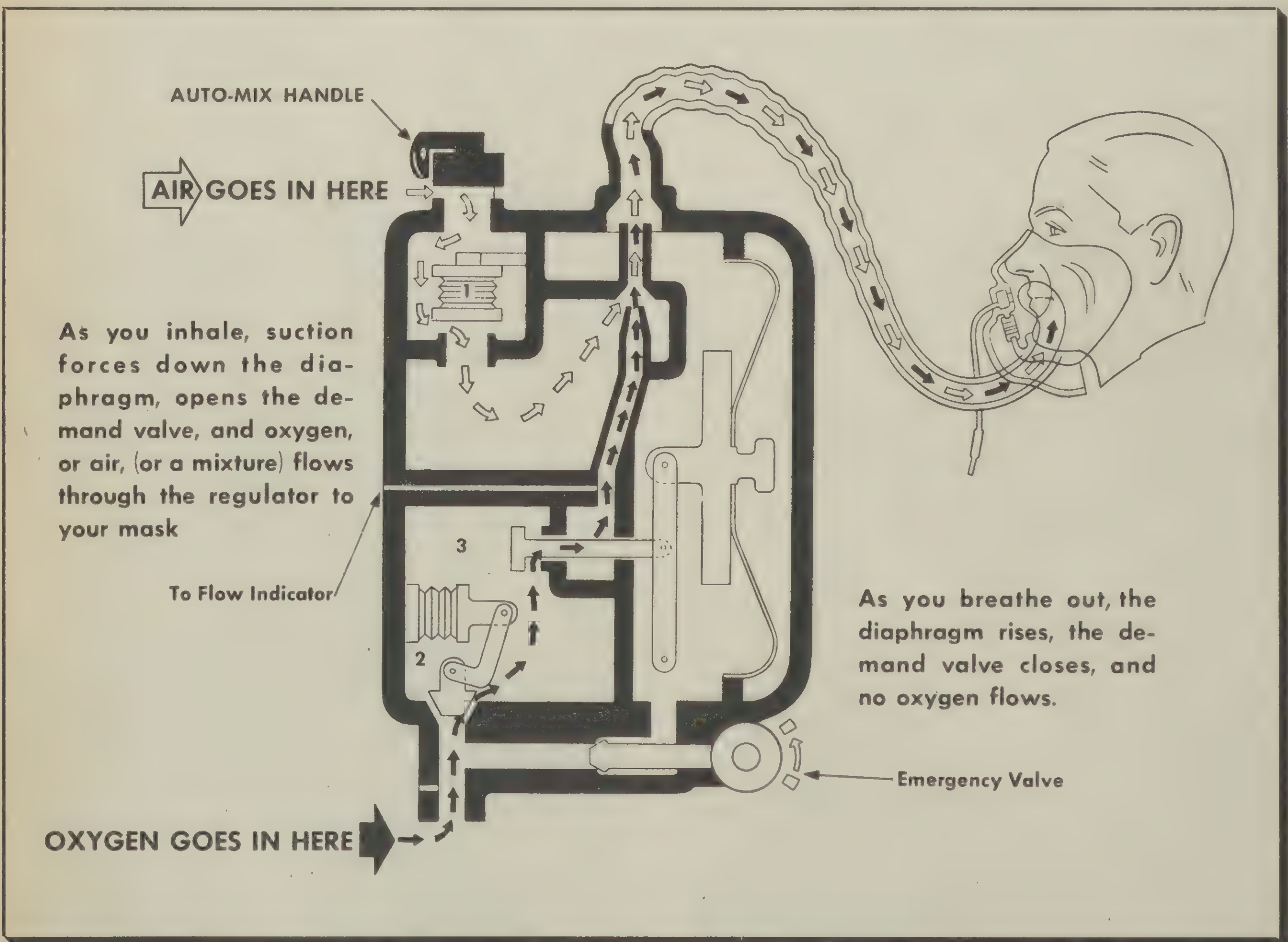


Figure 20.—Demand valve operation in Pioneer design A-12 regulator, Auto-Mix "ON" ("NORMAL OXYGEN").

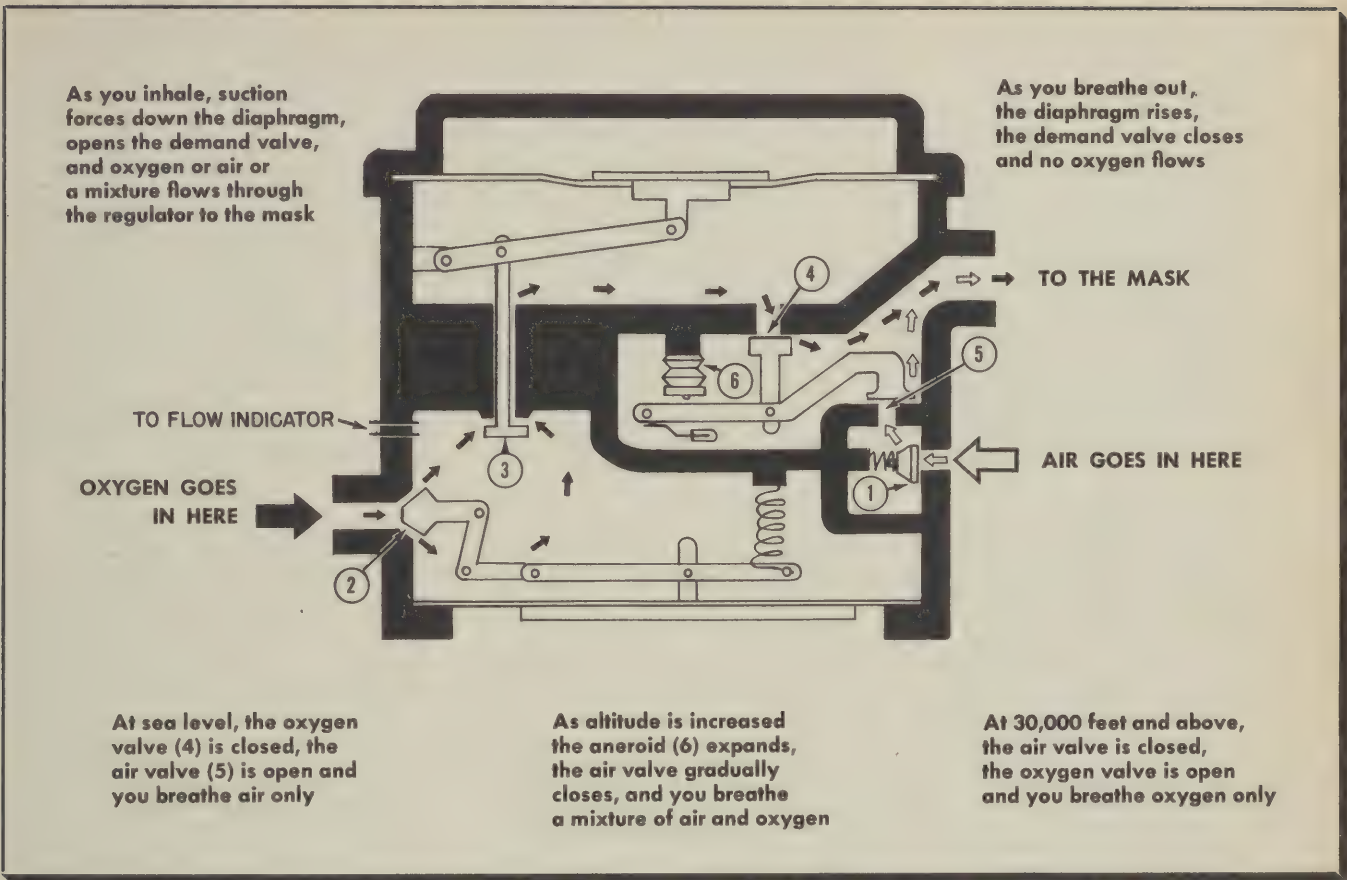


Figure 21.—Demand valve operation in Airco design A-12 regulator, Auto-Mix "ON" ("NORMAL OXYGEN").

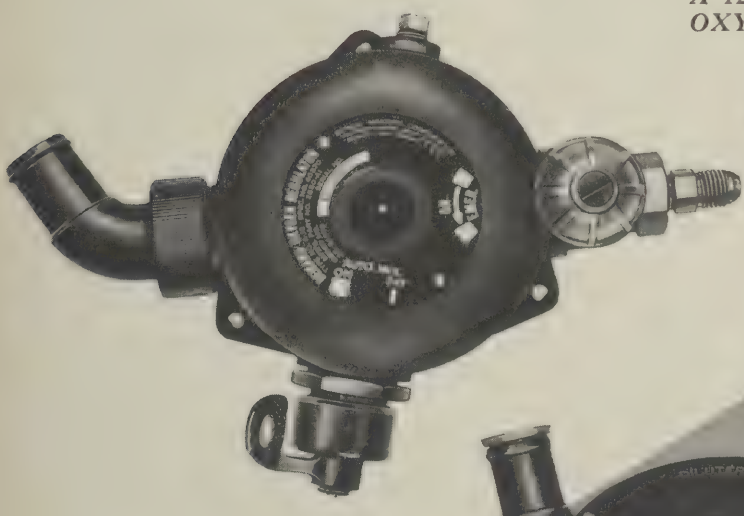


Figure 22.—Diluter-demand regulator, type A-12, Pioneer design.

Figure 23a.—Diluter-demand regulator, type AN 6004-1, Aro design.

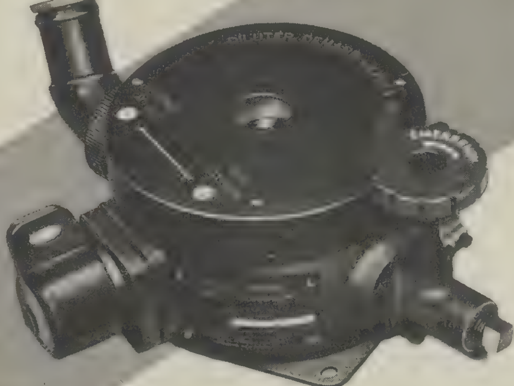


Figure 23b.—Diluter-demand regulator, type AN 6004-1, Pioneer design.

Figure 24.—Development of the demand oxygen mask — a. type A-9; b. type A-10; c. type A-10 Revised; d. type A-14; e. type A-10A.

mask, inboard leaks of air into the mask must be avoided. Development of the AAF mask is shown in figure 24. The first demand mask was developed at the Harvard School of Public Health under the auspices of the NDRC. This mask was subsequently modified by the AAF. The present demand mask was developed in conjunction with the AAF by Dr. A. H. Bulbulian of the Mayo Clinic.

The original demand mask was known as the L-12. When adopted for AAF use, this model was modified and designated the A-9. The A-9 was issued in two sizes, large and small. It was soon found that the suspension was not adequate to hold the mask in place during high G maneuvers, that the expiratory valve was small, and that the mask was difficult to fit, especially about the nose. Basically, the L-12 introduced the principle of bringing oxygen into the mask through two ports situated high in the mask to prevent moisture from collecting in them, and the principle of insulating the expiratory valve with expired air.

The major difficulties experienced with the A-10 mask were in the complexity of suspension and difficulty in fitting. The suspension was changed in the revised A-10.

The A-14 mask was introduced because of its increased comfort and ease in fitting. It was followed by a modification of the A-10R to the A-10A. The A-10A was used to supplement production of the A-14.

Demand oxygen masks will generally function satisfactorily above —40° F. Below —40° F freezing may occur and can be partially remedied by a hood and eliminated by an electrical heater (figures 25a and b). The A-14 mask (figure 25c) has been altered by a modification designed to prevent freezing, originally proposed by the Eighth Air Force.

PRESSURE DEMAND SYSTEM.—For aircraft that operate above 35,000 feet a version of the demand system known as the "pressure demand system" has been developed. In this system two masks are used, the A-13 and A-15 (figures 26a and b), which seal against a positive pressure. The regulator, type A-14, is a version of the AN 6004-1 Aro regulator. A spring mechanism for depressing the diaphragm is geared to a knob calibrated in thousands of feet (figure 27). A compensating exhalation valve built into the mask permits the user to breathe against a positive pressure of from 1 to 12 inches of water, depending upon the degree of depression of the regulator diaphragm (figure 28). Oxygen does not flow during exhalation. Aside from the posi-

Figure 25a.—Hood for demand mask.

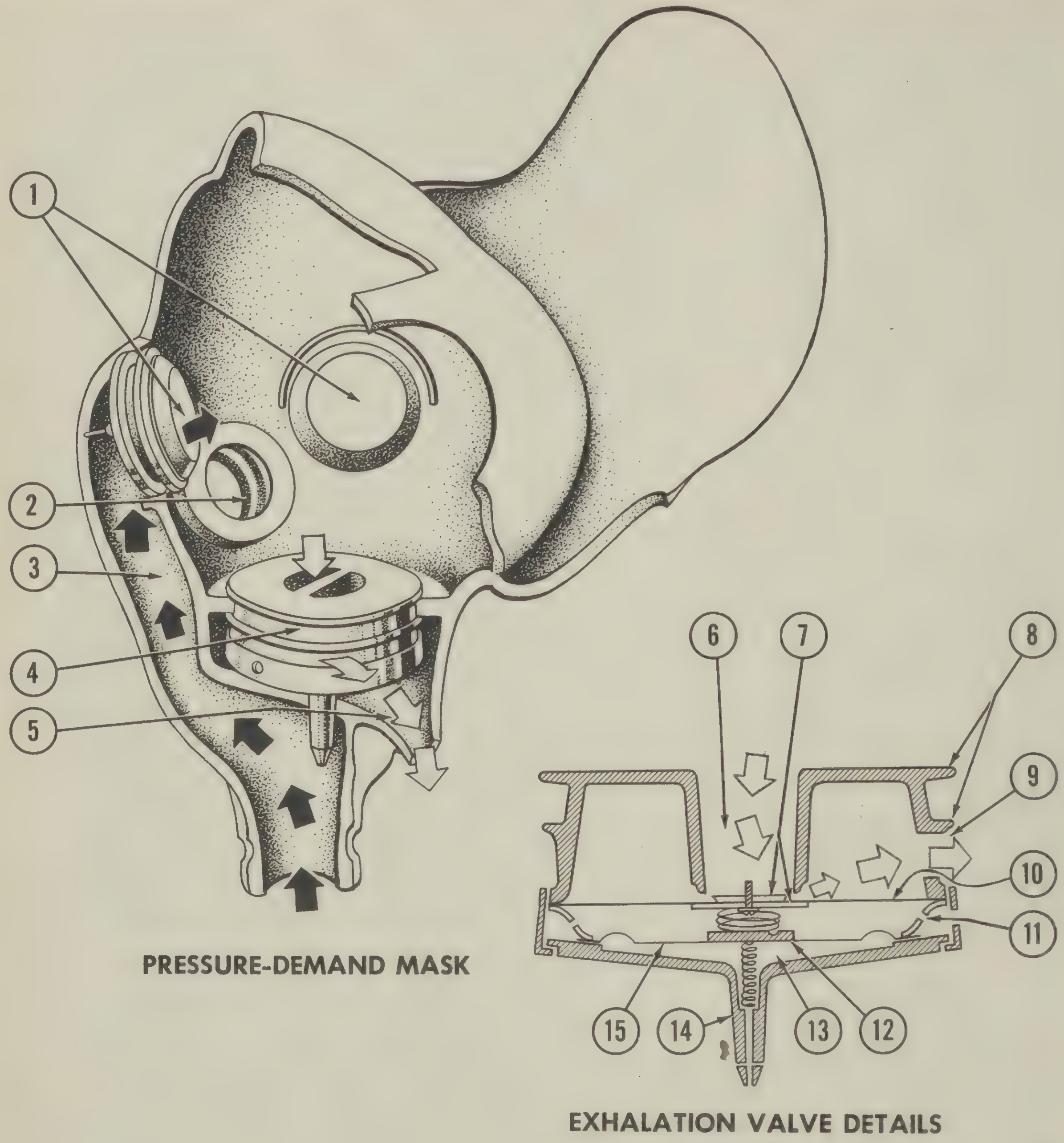
Figure 25b.—Heater for demand mask.

Figure 25c.—Inhalation baffle designed to prevent freezing around oxygen inlet ports of A-14 mask. The simple rubber flap may be installed easily and permanently by means of two studs, as illustrated.

Figure 26a.—Pressure breathing demand mask, type A-13.

Figure 26b.—Pressure breathing demand mask, type A-15.

Figure 27.—Pressure breathing diluter-demand regulator, type A-14.



1. Inlet Valves
2. Recess for Microphone
3. Inlet Port to Mask
4. Exhalation Valve
5. Outlet for Exhaled Air

OXYGEN

EXHALED AIR

6. Exhaled air enter exhalation valve here
7. These plates stiffen the main diaphragm
8. Projections on valve housing which seat in mask
9. Exhaled air leaves the valve here
10. Main diaphragm
11. This port permits pressure between the two diaphragms to equalize with the outside atmosphere.
12. This cup holds hairspring in place between the two diaphragms
13. Oxygen supply pressure is exerted in this "compensating" chamber
14. This tube sticks down into the mask inlet
15. This "compensating diaphragm" responds to oxygen supply pressure by pressing up against the main diaphragm

Figure 28.—Diagram showing operation of pressure-demand mask and exhalation valve.

tive pressure feature, for example, when the diaphragm of the regulator is in its normal position, the system operates as a conventional demand system. Figures 29a, b, c, and d show diagrammatically the operation of the A-14 regulator. Details of the pressure breathing demand system may be found in Technical Order No. 03-50-31, 30 July 1944.

The purpose of pressure breathing demand equipment is twofold. Minimal positive pressure may be employed between 35,000 and 40,000 feet to prevent inboard mask leaks and thereby insure delivery of 100 percent oxygen to the respiratory tract. Higher pressures may be utilized to increase the partial pressure of oxygen in the alveoli, thus insuring the flyer satisfactory oxyhemoglobin saturation at altitudes where conventional demand equipment would prove inadequate.

Oxygen Duration in Aircraft

Oxygen duration, or the length of time a given cylinder will last at altitude, is calculated simply for continuous-flow regulators. The flow is fixed within small limits and the only major variable which may cause error is the temperature of the cylinders.

In the demand system, however, duration is more difficult to predict, since the oxygen flow is in accordance with the demand of the individual. Consumption data for the demand system are influenced by the following factors:

1. The oxygen concentration delivered by the regulator. This differs in the two types of regulators, and varies slightly in any given regulator with rate of flow.

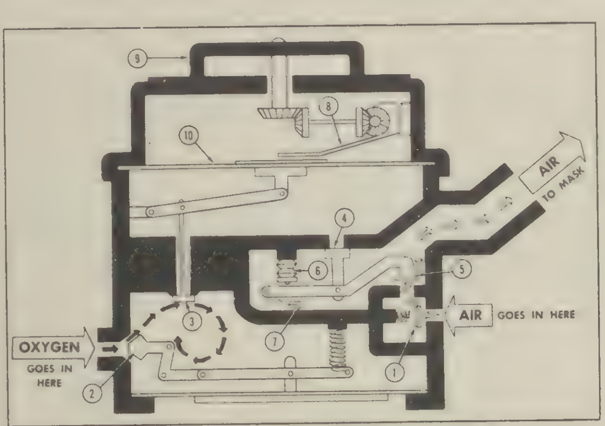


Figure 29a.—A-14 regulator operation during inhalation at sea level. Oxygen diluter valve (4) is closed; air diluter valve (5) is open, and you breathe air only.

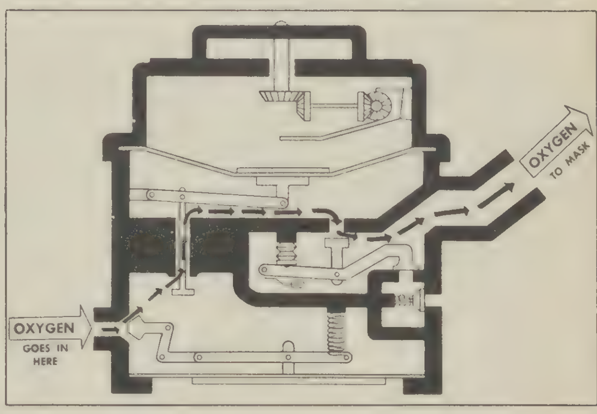


Figure 29b.—Regulator operation during inhalation at 30,000 feet. Air diluter valve (5) is closed; oxygen diluter valve (4) is open, and you breathe 100 percent oxygen.

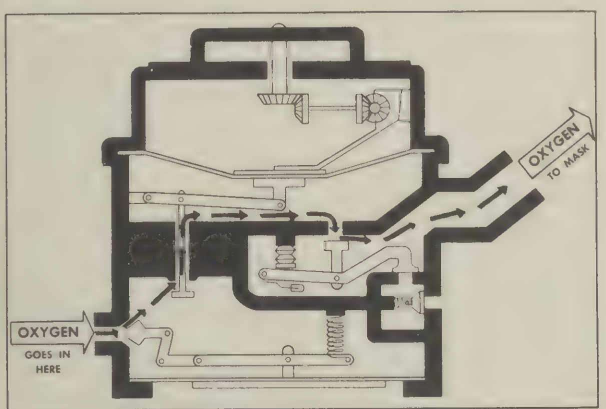


Figure 29c.—Regulator operation during inhalation with pressure breathing. Spring (8) presses down on diaphragm, opening demand valve (3) and forcing oxygen into the mask under pressure.

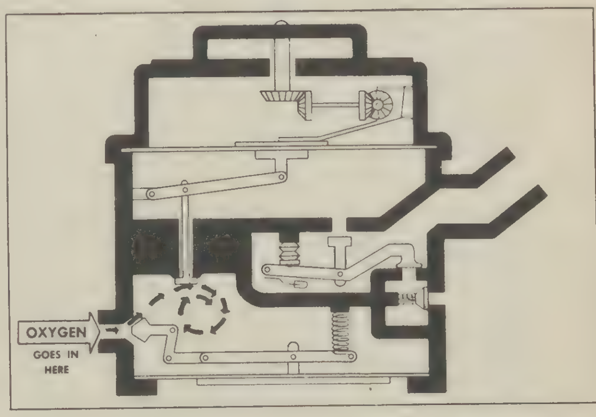


Figure 29d.—Regulator operation during exhalation with pressure breathing. As you exhale you momentarily raise the pressure in the mask above the oxygen supply pressure, forcing the diaphragm up against the spring tension. The demand valve (3) closes and no oxygen flows.

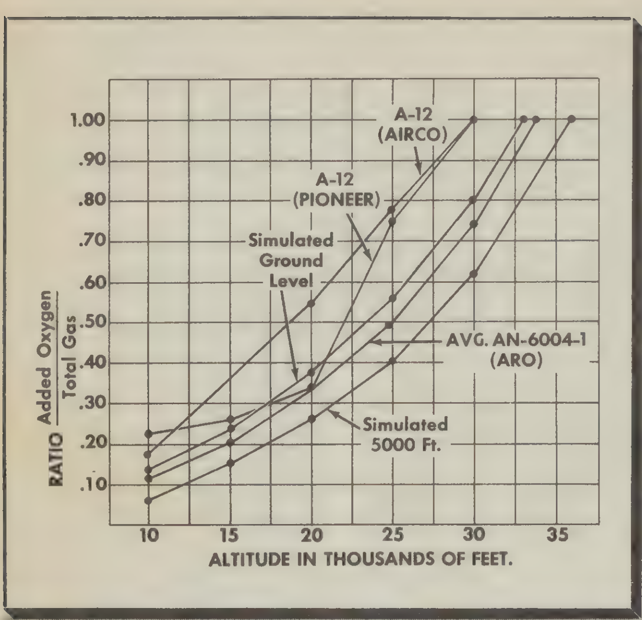


Figure 30.—Dilution characteristics of diluter-demand regulators. The curve for the A-14 pressure breathing regulator would be the same as that for the AN 6004-1.

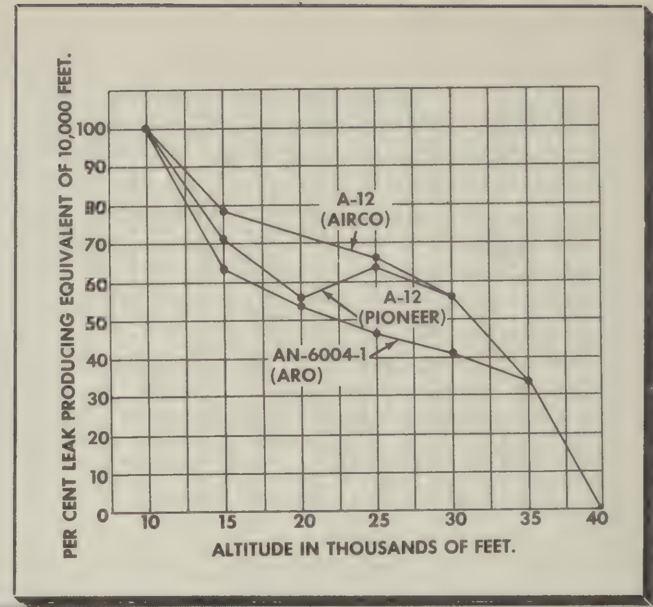


Figure 31.—Calculated mask leak required to produce physiological equivalent of 10,000 feet altitude with Auto-Mix set to "ON" or "NORMAL OXYGEN." The curve for the A-14 pressure demand regulator when used without pressure would be the same as that for the AN 6004-1 regulator.

2. The temperature of the cylinders.

3. The oxygen consumption of the individual. This varies from 8 to 60 liters per minute depending on the activity of the individual.

Since 1943 the AAF has used the value of 14.2 liters per minute inspired volume for duration calculations. Calculations are made as follows:

$$\text{Duration in hours} = \frac{\frac{P}{14.7} \times V_C \times N_C}{\dfrac{V_C}{\frac{B_A - 47}{B} \times \frac{T}{T_B} \times F_{O_2} \times 60 \times N_M}}$$

Where P=pressure change at constant temperature

V_C=volume of cylinder in liters

N_C=number of cylinders

F_{O_2}=fraction of cylinder oxygen delivered by the regulator

T_B=temperature of body (absolute)

T=temperature of cylinder (absolute)

B_A=pressure at altitude in mm Hg

B=760 mm Hg

N_M=number of men

In Technical Orders the temperature of the cylinder is assumed to be 20° C. Since no accurate determination of the cylinder temperature can be made at altitude, no further correction is attempted. This introduces an error in the positive direction. In all graphs average values of Pioneer regulators or Airco regulators are used, selection being made of the greater amount.

Actual combat data from over 4,000 fighter-bomber sorties and 150 bomber sorties indicate that duration predictions were higher than the actual consumption in 70 to 80 percent of the missions.

PERFORMANCE OF DEMAND OXYGEN REGULATORS.—The characteristics of diluter-demand regulators are shown in figure 30. Although oxygen is not required below 10,000 feet in daylight flying, the minimum requirement for regulators is set at 5,000 feet simulated altitude. Later-type regulators (AN-R-5) are more economical and conform more nearly to required standards.

Mask leakage has decreased since the standardization of the A-14 mask. Nonetheless, proper fitting of masks cannot be overemphasized. Instantaneous leaks can and do occur, but they are compensated for, to some extent, by the excess oxygen delivered through the regulator. Figure 31 compares the three types of regulators in this regard. A-12 regulators (with the exception of the Pioneer at 20,000 feet) deliver sufficient oxygen to compensate for relatively large leaks. Adequate compensation can be introduced only by utilizing a slight positive "safety" pressure which again necessitates adequate mask fitting to preserve economy. Economy is a great factor in AAF planes and must be balanced against other elements. This has led to the standardization of the later-type (AN-R-5) regulator. Suctions encountered in the regulators are shown in figures 32a and b and correlated with flow and altitude.

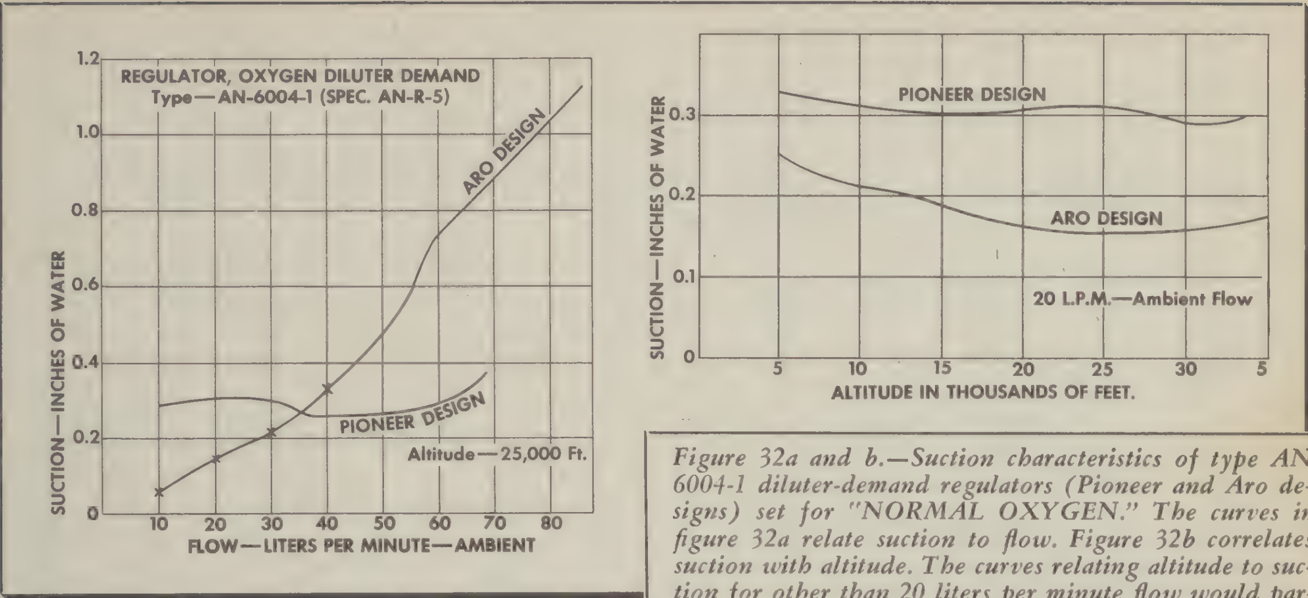


Figure 32a and b.—Suction characteristics of type AN 6004-1 diluter-demand regulators (Pioneer and Aro designs) set for "NORMAL OXYGEN." The curves in figure 32a relate suction to flow. Figure 32b correlates suction with altitude. The curves relating altitude to suction for other than 20 liters per minute flow would parallel those in figure 32b. The initial points for such curves may be taken from figure 32a.

CHAPTER IV

EFFECTS OF LOW BAROMETRIC PRESSURE

Decreased barometric pressure, in addition to causing anoxia, has certain undesirable direct effects upon the body, generally termed "decompression sickness." These direct effects may be divided, according to basic physical mechanism, into two groups:

1. Effects due to entrapped gases. During ascent the expansion of free gas in certain body cavities from which escape is not readily available may lead to abdominal pain, toothache, or pain referable to the sinuses.

2. Effects due to evolved gases. During flights at higher altitudes, primarily those above 30,000 feet, gases (principally nitrogen) which have escaped from solution in blood and tissue fluids may be responsible for the syndrome known as aeroembolism.

These conditions will be better understood if certain physical laws are briefly reviewed.

Basic Physical Laws

During ascent, the volume of any free gas within the body tends to increase in accordance with Boyle's law, which states that the volume of a gas is inversely proportional to the pressure exerted upon it. Gases within the body, however, are saturated with water vapor at 37° C. This means that the external pressure must be corrected by subtracting 47 mm of mercury, the vapor pressure of water at body temperature. As a result the expansion of a given quantity (sea level volume) of saturated gas in a body cavity is greater at a given altitude than that of an equal quantity of dry gas.

The comparative volumes of gases inside the body at various altitudes are shown in table 4 and in figure 33.

TABLE 4

COMPARATIVE VOLUMES OF GASES (SATURATED AT 37°C*) INSIDE THE BODY AT VARIOUS ALTITUDES

Barometric pressure, mm Hg	*inches*	*Altitude, feet*	*Relative volume of gas saturated with water vapor*
760	29.92	0	1.0
635	25.40	5,000	1.2
523	20.92	10,000	1.5
429	17.16	15,000	1.9
349	13.96	20,000	2.4
282	11.28	25,000	3.0
226	9.04	30,000	4.0
179	7.16	35,000	5.4
141	5.64	40,000	7.6

*Pressure of aqueous vapor at 37°C is 47 mm Hg.
Example of calculation:

$$\frac{760-47}{523-47} \quad 1.5$$

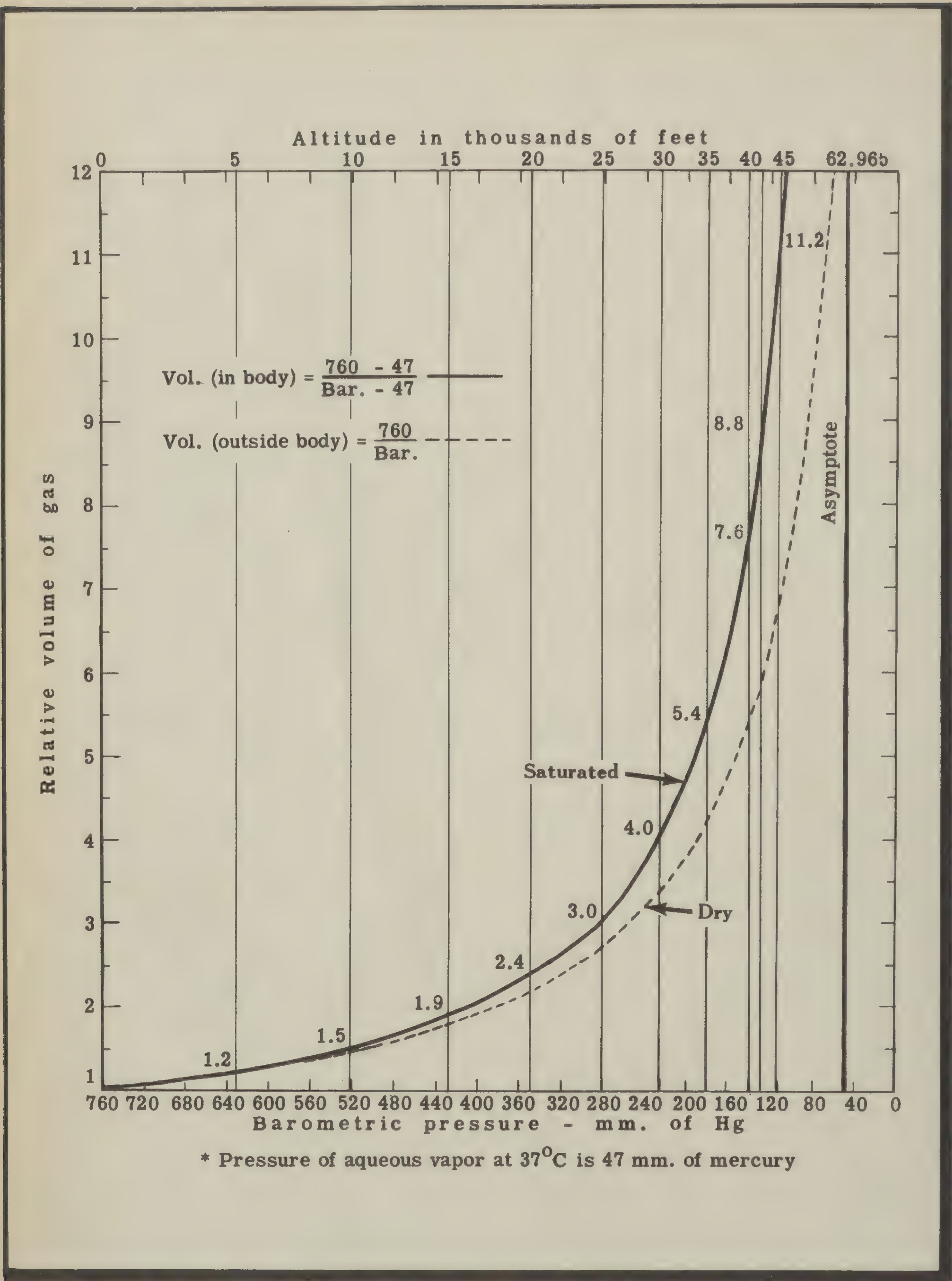


Figure 33.—Comparative volumes of gases (saturated at 37°C or 98.6°F) inside the body at various altitudes.

Within the body an appreciable quantity of gas is in simple solution. Even in as complex a system as the body, the factors which influence the amount of gas in solution can be reduced to three:

1. The nature of the gas.
2. The nature of the solvent (body liquids).
3. The partial pressure of the gas.

These factors will be considered in more detail in connection with aeroembolism.

Effects on the Gastrointestinal Tract

One of the most frequently experienced direct effects of rapid decrease in atmospheric pressure is the discomfort caused by the expansion of gas within the digestive tract. Fortunately, the symptom is not serious in most individuals. In flights above 25,000 feet, however, enough distention may occur to produce severe pain.

The stomach and the small and large intestines normally contain a variable amount of gas which is always maintained at a pressure approximately equivalent to that of the atmosphere surrounding the body. Considerably more gas is contained in the stomach and large intestine than in the small intestine. The chief sources of this gas are swallowed atmospheric air and, to a lesser extent, gas formed as the result of digestive processes —fermentation, bacterial decomposition, and putrefaction of food which is undergoing digestion. Gases normally present in the gastrointestinal tract are oxygen, carbon dioxide, nitrogen, hydrogen, methane, and hydrogen sulfide. These occur in varying proportions although the highest percentage of the gaseous mixture is always nitrogen.

As gases in the stomach and intestine expand with altitude (figures 34a and b), relief is ordinarily obtained by belching and the passing of flatus. If relief were not obtained in this fashion, extreme discomfort would result, and, at very high altitudes, there might well be interference with respiration caused by elevation of the diaphragm; with the initial volume of one liter of gas, the volume of such gas would be 1.5 liters at 10,000 feet, 3 liters at 25,000 feet, 7.6 liters at 40,000 feet, and 17 liters at 50,000 feet.

During ascent at higher rates of climb, such as 1,000 feet or more per minute, abdominal distention is increased considerably and one may begin to suffer abdominal cramps of varying severity at altitudes as low as 15,000 to 20,000 feet. With such rates of climb these cramps occur often at 30,000 to 35,000 feet, and relief of symptoms is more difficult to achieve at altitude. Walking and moving about in the decompression chamber, or in aircraft in which this is possible, frequently aid the expulsion of gas.

Recent studies have caused some doubt concerning the nature of the hitherto accepted mechanism of gastrointestinal pain at high altitude. From these later investigations it appears that abdominal pain due to decompression does not depend upon the absolute volume or location of intestinal gas. It is possible that sensitivity or irritability of the individual's intestine is more important and that this may vary from time to time, depending upon such factors as fatigue, apprehension, emotional tone, and general physical condition. Though gas-forming foods probably have little direct influence on the production of abdominal symptoms at altitude, it is possible that in certain individuals specific types of

Figure 34a.—X-ray photograph, taken from the front of the body, of the stomach at ground level, after the introduction into the stomach of 200 cc of gas.

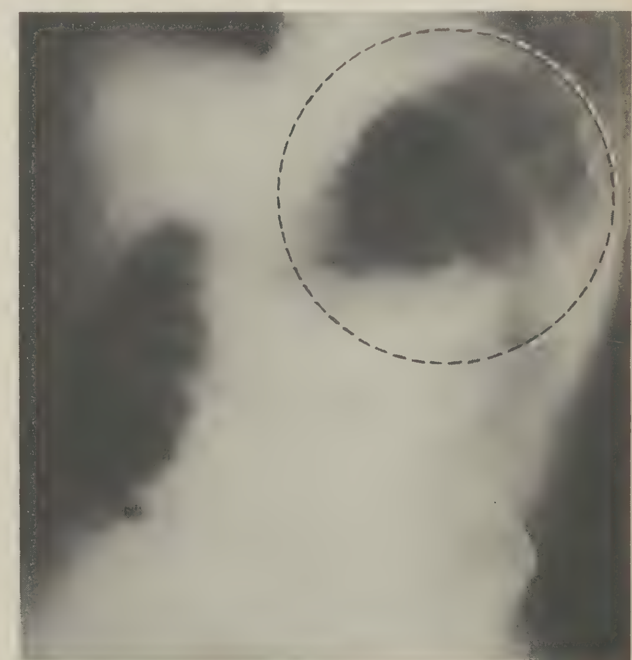


Figure 34b.—Appearance of the stomach in figure 33a as seen at a simulated altitude of 40,000 feet. Air shows as a darker area in the photograph.

food may alter the sensitivity of the intestinal tract to gaseous distension and cause symptoms.

PREVENTION OF DISTRESS.—It is obvious that, especially before going to high altitude, flyers should avoid any foods which they know to "disagree with them." Such foods are most commonly onions, cabbage, raw apples, radishes, dried beans, cucumbers, and melons. Before high altitude missions, it is advisable to avoid large quantities of fluid, especially carbonated beverages and beer. Gum should not be chewed during ascent as air is often unavoidably swallowed.

Insufficient attention has been paid to eating habits in connection with gas pains at altitude. Eating irregularly, hastily, or while at work makes the individual much more susceptible to gas pains. It has been noted during flights in low-pressure chambers that individuals who have not eaten at all for 12 to 24 hours often suffer severe gas pains. At bases where the schedule is very strenuous and irregular, and the flyers have to eat hastily and at irregular intervals, low-pressure chamber records show that the number of men who cannot tolerate high altitude because of gas pains may be 10 times as great as in groups living normally. Under such conditions gas pains present a more serious problem than bends. It is recommended that groups of men who are to fly at high altitude receive special consideration with reference not only to diet but also to conditions under which the food is eaten.

Effects on Ears, Sinuses, and Teeth

On ascent the air within the middle ear usually escapes without difficulty through the Eustachian tube, and pressure is released from the paranasal sinuses into the nasal cavity. Maintaining middle-ear pressure on a level with the ambient pressure is more difficult during descent than during ascent. Sinuses and teeth may be adversely affected during descent as well as in ascent. For these reasons a full discussion of the problems is reserved for a special chapter.

Aeroembolism

DEFINITION.—Aeroembolism, known also as "decompression sickness," "bends," and "aeroemphysema," is a condition produced by exposure to low atmospheric pressure (high altitude) and is characterized by the formation of bubbles (consisting of nitrogen, oxygen, carbon dioxide, and water vapor) in the tissues, blood, and other fluids of the body. Its causative factors are fundamentally the same as those of bends in caisson workers or deep-sea divers.

ETIOLOGY.—The formation of gas bubbles within the human body is similar to the release of bubbles in a bottle of charged water or beer when the cap is removed. In the manufacture of charged water, carbon dioxide under pressure is forced into the fluid at the time of filling and goes into solution. It remains in solution because the bottle is capped. When the cap is removed the gas comes out of solution because its pressure is higher than that in the outside air to which it is exposed. If the cap is replaced, pressure is built up in the space between it and the fluid level below until the gas in that space and the gas in solution are in equilibrium, at which time bubbling ceases. If a container of tap water is taken to high altitude, gas bubbles like those in bottles of charged water start to form at approximately 18,000 feet and are very evident before an altitude of 30,000 feet is reached.

Tissues and fluids of the body contain dissolved nitrogen. Though under ordinary conditions from 1 to 1.5 liters of dissolved nitrogen is present in the body, the amount in solution depends on the pressure of nitrogen in the air. This, in turn, depends on altitude. If altitude is raised, a new equilibrium is established, and nitrogen leaves the body. If the change is rapid, there is a lag in the attainment of equilibrium, leaving the body temporarily supersaturated with nitrogen. Thus, in rapid ascents to high altitudes the amount of dissolved nitrogen in the body is in excess of that which can be held in solution. The nitrogen in tissues bathed by the blood ordinarily finds its way into the capillaries and is carried in the blood stream to the lungs where it is eliminated. When ascent to altitudes of 30,000 feet or more is rapid, however, the nitrogen tends to come out of solution and form bubbles in the tissues and in the blood. In addition to nitrogen, the bubbles contain smaller quantities of carbon dioxide, oxygen, and water vapor. The tissues which have the highest content of fat are most favorable for bubble formation since fat per unit of mass dissolves five or six times more nitrogen than does blood.

INCIDENCE.—The frequency and severity of aeroembolism vary with these factors: (1) rate of ascent, (2) altitude attained, (3) time at altitude, (4) environmental temperature, (5) bodily activity, (6) age, (7) body build, and (8) individual susceptibility.

In general, the more rapid the rate of ascent, the sooner the symptoms appear. At altitudes of less than 30,000 feet, however, the incidence of aeroembolism is very low, regardless of the rate of climb. Above this altitude symptoms may occur even though the rate of ascent has been low. Aeroembolism may develop during ascent or while the plane is leveled off at altitude. Under the latter condition the symptoms ordinarily do not develop immediately. The latent period varies greatly but practically never is greater than four hours. In general, the incidence and severity of symptoms vary directly with the length of the stay at altitude.

The effect of environmental temperature on the incidence of aeroembolism has not been definitely established. It has been reported that local heating lessens the pain in bends. On the other hand, in tests conducted at simulated altitudes of 38,000 feet, with subjects wearing protective clothing suited to the environmental temperature, the incidence of bends was less at —40°C than at 25° C. It is not known whether the symptoms of aeroembolism would be made more severe by actual chilling of the body.

Physical exercise lowers the altitude threshold for bends, often causing attacks in simulated flights to 26,000 feet; instances have been reported at 22,000 feet. The reasons for this are not known. The performance of prescribed exercises at altitude has been used to increase the reliability of tests for susceptibility to aeroembolism.

Analysis of data procured to date has revealed the incidence of aeroembolism to be related to age and to body build as measured by surface area or by weight: height ratio. In general, the occurrence of symptoms increases with age and with body surface area (or ratio of weight to height). It would appear, therefore, that the youngest and smallest men available might best be chosen for prolonged missions at the higher altitudes. The whole problem of individual susceptibility has been the subject of much study. The goal has been a reliable classification procedure which would select air crews of high resistance. In general, the results have not been very successful. It has been found that repeated flights in a low-pressure chamber show that a few people are chronically susceptible to one or more forms of aeroembolism, and that a few are highly resistant. The reaction of a majority of flyers, however, is unpredictable for a given flight. The practical result obtained is elimination of the few individuals who obviously are unfitted for high altitude flight because of a high degree of susceptibility to severe symptoms of aeroembolism. To date the majority of operational flights have been below an altitude at which incapacitating aeroembolism occurs. Although fighter aircraft have gone above 30,000 feet, flights usually are of such short duration that aeroembolism has not been a problem. If operations, particularly those of long duration, are to be carried out above that altitude, denitrogenation to prevent aeroembolism will be necessary.

Incidence of Aeroembolism in Flight.—Since the large program of indoctrination in decompression chambers has been under way, flyers have often raised the question of the relationship of the symptoms of aeroembolism they have experienced in the chamber to those that might occur in flight. The opinion often is expressed that in flight symptoms are not likely to occur. Data on actual flights are limited, but records of several hundred man-flights at or above 30,000 feet for one to three hours indicate that the incidence of bends is about the same and the symptoms are no greater than those experienced by the same individuals in the low-pressure chamber.

In general, flights in the low-pressure chamber involve higher altitudes than most of those in aircraft. The chief contributing factor in producing bends at altitude is exercise. Therefore it is to be expected that individuals who engage in heavy work during flight are more likely to get bends than those who sit quietly in a chamber at the same altitude.

GENESIS.—In spite of intensive research, there is still much to be learned about the actual pathological changes which occur in aeroembolism, and about its pathogenesis. The term itself is rather misleading, as embolism implies that the fundamental pathological process takes place in the blood vessels. Actually, the formation of bubbles occurs first in the other tissues and later in the blood. It is believed that the formation of bubbles is most likely to occur in regions which are supersaturated with nitrogen; that is, in relatively nonvascular tissues with a high content of fat. The exact mechanisms by which the symptoms are produced are not fully understood, but most evidence seems to indicate local rather than central nervous irritation.

No adequate explanation of, or evidence for, a mechanism involving direct irritation has been provided. However, since there is evidence that ascent to altitudes above 30,000 feet is accompanied by arteriolar spasm, such vasospasm must be considered as a possible factor in the production of aeroembolic symptoms.

SYMPTOMS.—The principal symptoms of aeroembolism are the following:

Bends. Pain in and about the joints may be mild at the onset, but often becomes deep, gnawing, and boring in character, and may become so severe that it is intolerable. Ordinarily the pain is progressive and becomes more severe if ascent is made to a higher altitude. In some cases, however, mild pain disappears after a few minutes or an hour. Severe pain can cause loss of muscular power of the extremity involved, and, if the pain is allowed to continue, it may result in collapse. The pain may diffuse from the joint over the arm or leg as a whole, or over the entire area of a long bone. It may, indeed, be referred primarily to muscle or bone rather than to a joint. The larger joints, such as those of the knee and shoulder, are most frequently affected. Others commonly involved are the small joints of the hands, wrists and ankles. In successive exposures there is a tendency for pain to recur in the same place. It also may occur in several joints at the same time and it is accentuated by movement and weight bearing. Coarse tremors of the fingers often occur if there is pain in one of the joints of the arm.

Although pain is more likely to occur in an extremity at the site of a fresh or recent injury, investigation of data has shown little correlation between bends and old injuries.

Chokes. Symptoms referable to the thorax, and commonly termed chokes, probably are caused in part by blocking of the smaller pulmonary vessels by innumerable small bubbles. This, at first, may cause a burning sensation underneath the sternum. As the condition progresses, the pain may become more severe, may be stabbing in character, and may be markedly accentuated upon deep inhalation. The sensation sometimes is described as being similar to that felt in the chest at the completion of a 100 yard dash. It is necessary to take short breaths in order to avoid distress. There is an almost uncontrollable desire to cough, but the cough is ineffective and nonproductive. Finally, there is a sensation of suffocation, breathing becomes progressively more shallow, and there may be cyanosis. Immediate descent is imperative when these symptoms occur. The condition, if allowed to progress, frequently results in

collapse and unconsciousness. Fatigue and weakness, as well as soreness in the chest, may persist for several hours after descent to ground level.

Skin Symptoms. Symptoms of the skin include tingling, itching, and cold and warm sensations. These symptoms are thought to be caused by the occurrence of bubbles locally or in the central nervous system where they may involve nerve tracts leading to the affected areas in the skin. Cold and warm sensations of the eyes and eyelids are sometimes experienced, as well as occasional irritation, itching, and gritty sensations. A mottled red rash may appear on the skin and, more rarely, a wheal accompanied by a burning sensation. Bubbles may occur just underneath the skin, causing localized swelling. When there is excess subcutaneous fat, soreness accompanied by edema may be present for one or two days in the region affected by aeroembolism. Skin manifestations of aeroembolism are not in themselves incapacitating or critical.

Neurological Symptoms. Symptoms resulting from the effects of aeroembolism on the nerves, although they do not occur as often as those already described, may be extremely varied and occasionally present bizarre clinical pictures. The most commonly reported symptom is impairment of vision due to scotomata or gross visual defects. This, like other neurological manifestations, occurs primarily during or after descent and usually does not persist for a period longer than 30 minutes after reaching ground level. Subjects sometimes notice a flickering or shimmering which may be associated with blind spots. A symptom commonly associated with neurological aeroembolism is dull, persistent headache. Other comparatively rare effects are partial paralysis, sensory disturbance, and aphasia, all of which are usually transient. Electroencephalograms obtained during the existence of these symptoms indicate changes in the electrical activity of the brain. This is especially interesting in connection with the observation that people subject to migraine who participate in simulated flights in the decompression chamber frequently suffer a typical migrainous attack, or other neurological symptoms, or both.

COMPARATIVE INCIDENCE AND SEVERITY OF SYMPTOMS.—The following may be said with relation to the comparative incidence of incapacitating symptoms of aeroembolism and their danger: Bends often occur in mild form, whereas chokes are always incapacitating, but the number of cases of incapacitating bends far exceeds that of chokes. Neurological symptoms, which like chokes and severe bends must be regarded as potentially dangerous, occur less frequently. Although any of the three may provide an important link in the chain of events leading to collapse at altitude, there is some evidence to suggest that chokes and neurological symptoms provide a greater predisposition to collapse.

COLLAPSE AT HIGH ALTITUDE.—Individuals suffering severe pain at high altitude because of bends, chokes, or gas expansion sometimes suffer collapse with many of the symptoms of surgical shock: pallor; cold sweat; alterations in pulse, blood pressure, and packed red cell volume; and, at times, nausea and vomiting.

The circulatory phenomena involved in collapse at altitude are discussed in chapter II. It should be noted here that the most dangerous aspects of severe reactions resulting from exposure to lowered barometric pressure are the latent period of from 1 to 6 hours which frequently precede the manifest appearance of clinical shock; and the consequent resistance to treatment of what may be, at this point, a full-blown vicious circle of peripheral circulatory insufficiency, tissue anoxia, and marked hemoconcentration. For these reasons it is urged that a subject suffering a severe reaction at altitude be observed for at least 6 hours following his return to ground level, even though he feels well.

Occasionally severe collapse results from pain that would seem quite tolerable on the ground. Obviously, the body is under considerable stress because of respiratory and circulatory adjustments and possibly because of unknown factors. The flyer should be aware of the fact that he cannot tolerate pain above 30,000 feet as well as he can at lower levels, and that, in spite of his courage, pain may produce more general symptoms leading to collapse. The commanding officer of the airplane, should be prepared to descend, if at all possible, when one of his crew reports an unbearable pain, since the shock which may result could be fatal. If symptoms of shock have appeared, the victim should receive the usual first-aid treatment for shock, and artificial respiration if necessary. It is most important that he should be kept in the supine position, given adequate oxygen, and be taken to an altitude as far below 30,000 feet as possible. It is difficult to know how often shock may have occurred in actual flights, but evidence in some accident cases indicates its possibility.

RELIEF OF SYMPTOMS.—Symptoms of aeroembolism may be relieved by descent to a lower altitude. As pressure is increased, the volume of the gas bubbles decreases and the pain disappears. Fortunately, from a tactical point of view, descent to a very low altitude is rarely necessary. Pain usually is relieved after a descent of only a few thousand feet. It almost always disappears by the time 30,000 feet has been reached, although occasionally it is necessary to go to 25,000 feet or lower. Usually complete relief is obtained, but sometimes fatigue and minor, residual local soreness may be felt for several hours after flight. When chokes occur, breathing may be slightly painful for several hours after return to ground level, but the subject usually is safe below 25,000 feet if descent is begun soon enough and if an abundance of oxygen is supplied. When chokes occur, descent should be made to as low an altitude as the tactical situation permits. Reascent should not be made after the pain of bends or chokes has been relieved. In almost every instance the pain reappears, and often it is much more severe.

It recently has been observed that the pain of bends may be relieved or completely alleviated during the application of pressure above the site of pain, employing either a sphygmomanometer cuff inflated to 50 mm of mercury or more, or direct digital compression of the

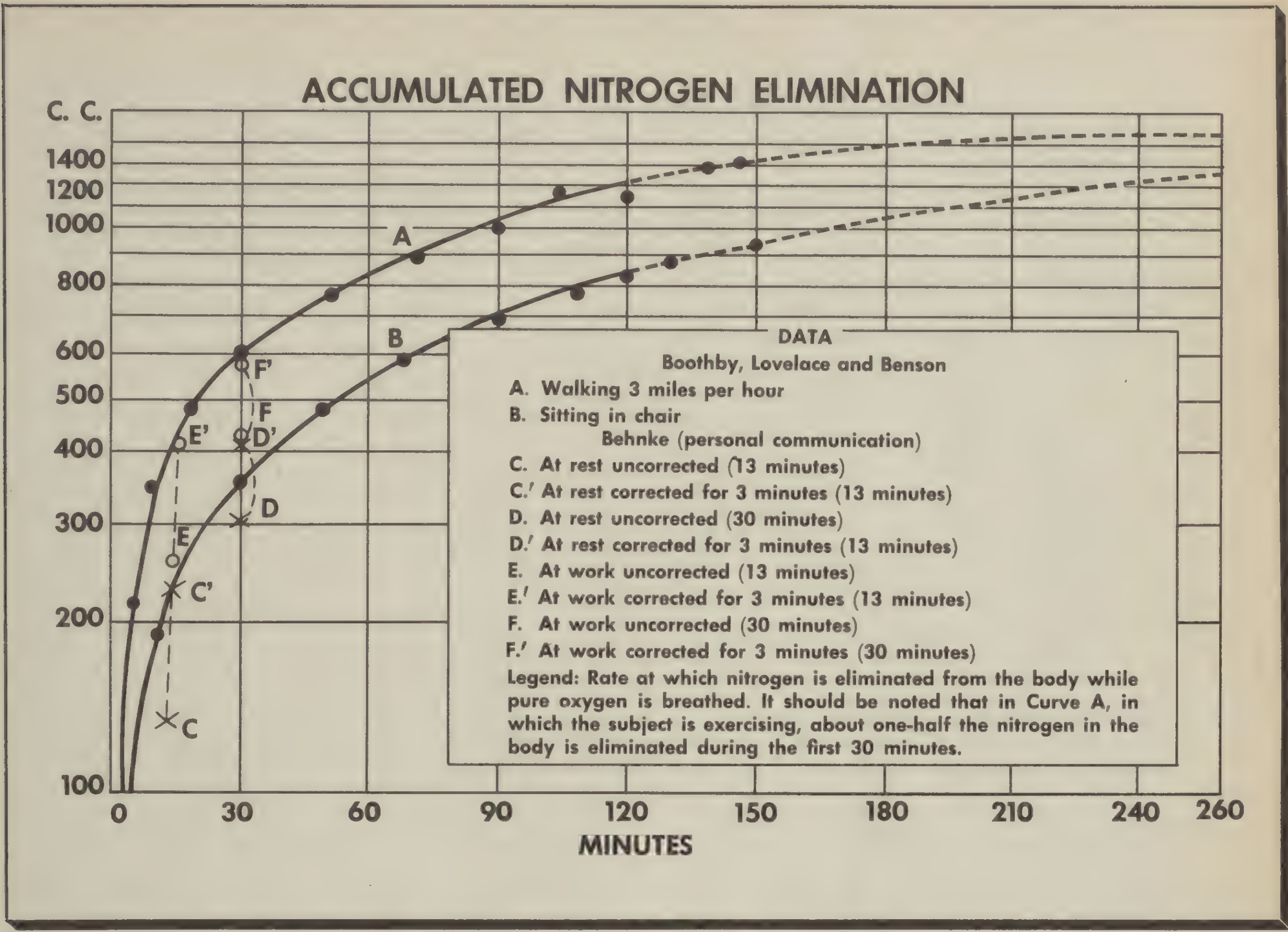


Figure 35.—Rate at which nitrogen is eliminated from the body while pure oxygen is breathed. It should be noted that in curve A, in which the subject is exercising, about ½ the nitrogen in the body is eliminated during the first 30 minutes.

artery. Although this has not yet received widespread trial, it represents an encouraging possibility in emergency treatment. The mechanism of relief of pain by this maneuver is not clear.

PREVENTION.—The most practical method for reducing the incidence of aeroembolism is to remove nitrogen from the body by breathing pure oxygen immediately before ascent, and by continuing to breathe pure oxygen from the ground up during ascent. Breathing pure oxygen tends to reduce the alveolar partial pressure of nitrogen to zero, thereby causing nitrogen in the body to flow from the tissues to the blood and into the lungs where it is expelled in the expired air (figure 35). It is not necessary to eliminate all the nitrogen from the body in order to gain adequate protection from aeroembolism. However, experiments have shown that the longer oxygen is breathed, the more protection may be expected. In one series of experiments with 251 cadets, it was found that breathing oxygen while at rest for 45 minutes before a chamber flight, involving a 2-hour stay at 38,000 feet, reduced severe symptoms from 30.3 percent to 5.8 percent (School of Aviation Medicine, Randolph Field, Texas). It has been recommended in the past that exercise be carried out while breathing oxygen on the ground before take-off. The experiments described above, and others carried out since at other laboratories, indicate that exercise is not necessary.

Breathing 100 percent oxygen from the ground up greatly increases the rate of consumption of oxygen; in some circumstances this may be prohibitive because of the limitation of the oxygen supply in the airplane. Aeroembolism, however, has not been a problem in combat operations up to the present, in most of which denitrogenation has not been employed. Flight surgeons who are called upon, in connection with special missions involving prolonged stays at high altitude, to give advice as to the necessity for denitrogenation and the methods for carrying it out should take into account the following facts: (1) Denitrogenation at any altitude up to 20,000 feet is fully as effective as it is at ground level; and (2) denitrogenation at altitudes between 20,000 and 30,000 feet is one-third to one-half as effective as it is at ground level.

Since physical activity at high altitudes increases the incidence of bends, such activity should be limited to that which is essential.

CHAPTER V

EFFECTS OF ASCENT AND DESCENT

Effect of Pressure Changes on the Ear

The ear functions as an organ of hearing and as one of the organs regulating equilibrium. Good hearing is essential to the proper use of aircraft radio and intercommunication systems and to the detection of abnormal engine sounds.

During flight, the ear is affected by changes in barometric pressure, by vibration, and by plane noise. In order to protect the ears as much as possible, the radio never should be tuned to a higher volume than is necessary, and, if aircraft noises are excessive, absorbent cotton plugs can be worn in the external auditory canal.

Anatomically, the ear (figure 36) is composed of the following: (1) the external ear and the auditory canal which terminates at the eardrum, a thin membrane about 0.004 inch (0.1 mm) in thickness; (2) the middle ear, located within the temporal bone of the skull, which consists of a small air space behind the eardrum and which communicates with the back of the nasal passages by means of the Eustachian tube; and (3) the internal ear, instrumental both for hearing and for equilibrium, and containing the cochlea, vestibule and semicircular canals. The external and middle ear conduct the air waves that produce the sensation of sound. Within the middle ear are three very small bones which form a chain between the drum and inner ear and conduct vibrations of the drum to the inner ear. The Eustachian tube, which permits communication between the cavity of the middle ear and the atmosphere, is a short slit-like tube which normally remains closed and which extends from the middle ear to the back wall of the throat (figure 37). Through this tube, air in the middle ear can escape or be replenished, thus averting discomfort by providing for the equalization of pressure between the air enclosed within the cavity of the middle ear and that in the surrounding atmosphere.

As the barometric pressure is reduced during ascent, the expanding air in the middle ear passes out, intermittently, through the Eustachian tube to the back portions of the nasal passages. As the pressure in the middle ear increases, the eardrum first bulges outward, until an excess pressure of approximately 15 mm Hg is reached, at which time a small bubble of air automatically is forced out through the Eustachian tube so that the pressure within the ear again becomes equalized with the outside pressure, and the eardrum resumes its normal position. Just before the air is forced out through the Eustachian tube, there is a sensation of fullness in the ear; as the pressure is released, there is often a click in the ear.

During descent in aircraft, the changes in pressure in the ear do not occur automatically, and much difficulty may be experienced in maintaining equalization of pressure in the middle ear with the pressure of the outside air. This results from the fact that the pharyngeal opening of the Eustachian tube acts as a flutter valve, allowing air to pass outward easily, but resisting its passage in the opposite direction. With an increase in barometric pressure during descent, the pressure of the external air rises above that inside the middle ear and the eardrum is forced in toward the middle ear. If the pressure differential is allowed to increase to an appreciable extent, it may be impossible to open the Eustachian tube, a condition which results in increasing pain and which eventually may result in rupture of the eardrum. When it is impossible to clear the ears, marked pain ensues and, if the pain increases with further descent, the only way in which relief can be obtained is by ascent to a level at which equalization of the pressure can be accomplished. A slow descent then is recommended. A rapid descent from 30,000 to 20,000 feet often will cause no discomfort, whereas a similar descent from 15,000 to 5,000 feet will cause great distress because the change in the barometric pressure is much greater in the latter case. In a descent from 18,000 feet to sea level, a difference in pressure of half an atmosphere may be produced; the eardrum, therefore, is forced in with a pressure equal to that of a column of mercury 38 cm (15.2 inches) high, which may well produce rupture of the eardrum. For this reason, special care is necessary in diving at low altitudes. When the eardrum is ruptured, it almost always will heal in a short time if it is kept clean and protected from infection, and usually there will be no impairment of hearing.

Normally, there is no difficulty in equalizing pressure during descent, for this can be accomplished by swallowing, yawning or tensing the muscles in the throat at intervals of about 1,000 feet. These procedures cause contraction of certain pharyngeal muscles which also open the pharyngeal orifices of the Eustachian tubes. If relief is not obtained by these maneuvers, air should be forced into the middle ear by closing the mouth, pinching the nose shut, and blowing gently, thus forcing air through the previously closed Eustachian tube into the cavity of the middle ear and equalizing the pressure. Repeated practice in clearing the ears rapidly improves the rate of descent which can be borne without discomfort. This has been illustrated dramatically in the low-pressure chamber, where experienced personnel can descend routinely at 10,000 to 30,000 feet per minute.

During sleep the normal swallowing reflex does not function; for this reason it is advisable to awaken sleeping passengers prior to descent in order to permit them to ventilate the middle ear in the usual manner.

It has been observed that personnel who have been breathing pure oxygen at high altitude for a considerable period, particularly if oxygen is breathed until ground level is reached, develop ear distress 2 to 6

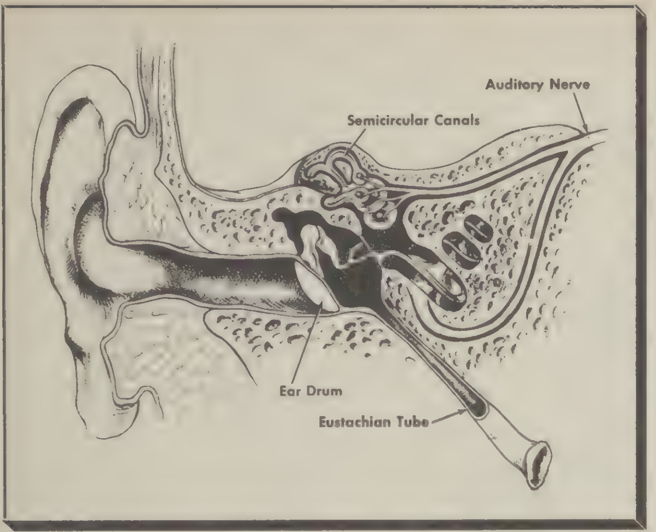


Figure 36.—Schematic representation of the ear.

hours after descent. If they are asleep the pain may awaken them. It is believed that this is the result of the practically pure oxygen in the middle ear being absorbed and thereby creating a decreased pressure in the middle ear. For this reason it is advisable to remove the oxygen mask at altitudes of less than 10,000 feet when descending from high altitudes in aircraft.

The most common subjective complaint of flyers is discomfort in the ears caused by inability to properly ventilate the middle ear. Such inability occurs most frequently when the Eustachian tube or its opening is swollen shut as the result of inflammation or infection coincidental with a head cold, sore throat, infection of the middle ear, sinusitis, or tonsillitis. In such cases, forceful opening of the tube may result in infected material being carried into the inner ear along with the air, causing disease of the middle ear. Therefore, flyers who have colds and sore throats should not fly unless it is absolutely necessary, and, if it is essential, they should endeavor to make slow descents, using a benzedrine inhaler or Nasalator (neosynephrin hydrochloride, 0.5 percent), which shrinks the membranes of the nose and throat and makes equalization of pressure easier.

Although upper respiratory infections are the chief offenders in producing narrowing of the Eustachian tubes, flyers with malposition of the temporomandibular joint may have ear pain and difficulty both in ventilating the middle ear and in hearing. In these cases, overclosure of the jaw presumably leads to relaxation of surrounding soft tissues and resultant mechanical narrowing of the Eustachian tube.

If the equalization of pressure has not taken place on landing, physicians usually can rectify the condition by the use of a spray, such as neosynephrin hydrochloride, 1 percent, which shrinks the membranes of the nose, or by having the flyer inhale ephedrine or benzedrine compounds. If a pressure chamber is available, reascent can be made to an altitude at which equalization can be accomplished.

When equalization of pressure cannot be accomplished during changes in barometric pressure, a condition occurs which has been named "aero-otitis media." This condition can be defined as acute or chronic traumatic inflammation of the middle ear caused by a difference of pressure between the air in the tympanic cavity and that of the surrounding atmosphere. It is characterized by congestion, inflammation, discomfort and pain in the middle ear, and may be followed by temporary or permanent impairment of hearing, usually the former.

Inflation of the middle ear often is effective for relieving aero-otitis. This procedure, however, should be accomplished only by a physician after full vasoconstriction has been induced in the nasal and nasopharyngeal mucous membranes. A constant flow of air is introduced through one nostril and the other nostril is occluded. When swallowing occurs, the soft palate is drawn upward and closes the nasopharynx from the oral cavity, thus allowing the compressed air to inflate the middle ear. The pressure must be controlled carefully so that it does not overinflate the middle ear or damage the intranasal structures.

Effect of Pressure Changes on the Sinuses

The paranasal sinuses (figure 38) present a condition in flight similar to that presented by the middle ear. The sinuses are air-filled, relatively rigid bony cavities

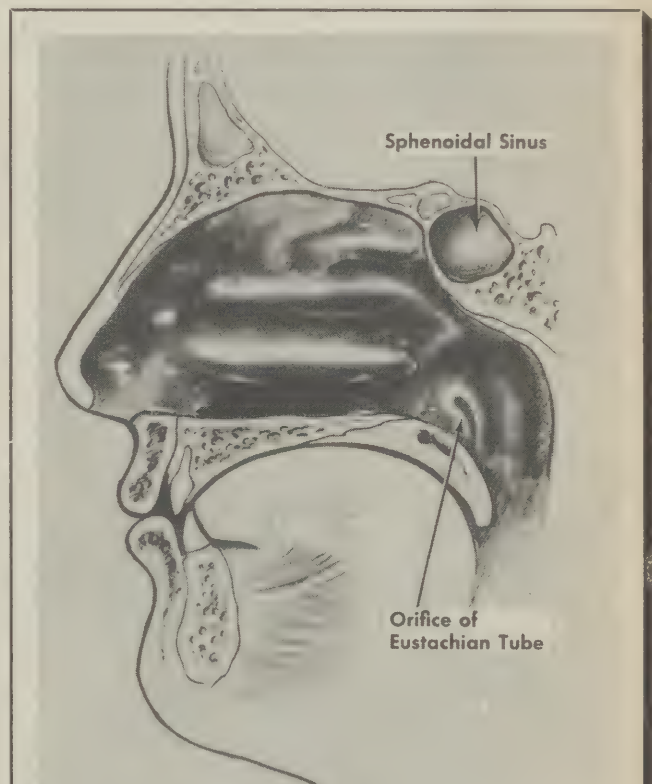


Figure 37.—Schematic diagram illustrating the orifice of the Eustachian tube.

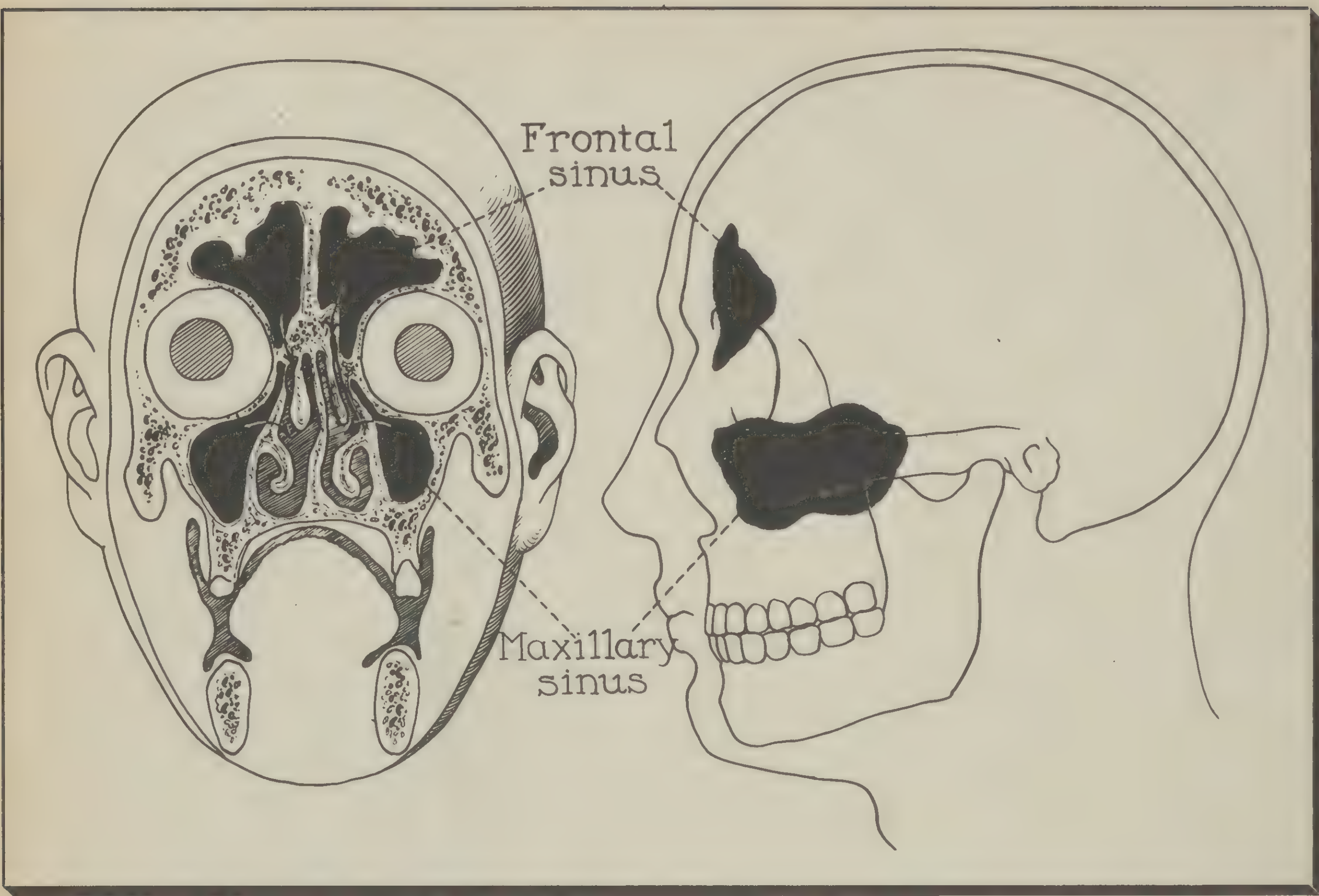


Figure 38.—Schematic representation of the paranasal sinuses.

lined with mucous membrane. They communicate with the nose by means of one or more small openings. Two of these sinuses are situated within the bones of the forehead, one within each cheek bone, and two in the bones just back of the root of the nose.

If the openings into the sinuses are normal, air passes into and out of these cavities without any difficulty at any practical rate of ascent or descent, thus assuring adequate equalization of pressure at all times. If the openings of the sinuses are obstructed by the swelling of their mucous membrane lining, caused by inflammation or an allergic condition such as hay fever, or if the openings are covered by redundant tissue on which viscous secretions are present, ready equalization of pressure becomes impossible. The pressure gradient that is established in change of altitude produces a pressure differential between the air inside and outside and causes marked pain. Unlike the ears, the sinuses are almost equally affected by ascent and descent.

If the frontal sinuses are involved, the pain extends over the forehead above the bridge of the nose; if the maxillary sinuses are affected, the pain is on either side of the nose, in the cheekbones. Maxillary sinusitis may produce pain referred to the teeth of the upper jaw, and may thus be mistaken for aerodontalgia.

The pain of aerosinusitis, though often of the same type as that caused by ordinary sinusitis at ground level, may be much more severe and fulminating in the event of sudden blockage during rapid change in altitude.

Equalization of pressure to relieve pain in the sinuses is best accomplished by yawning, swallowing, or blowing with the nose and mouth closed.

Treatment of aerosinusitis should be directed to the obstructed orifices, which usually can be opened by shrinking the nasal mucous membranes with those preparations normally used for this purpose, such as the familiar benzedrine inhaler or a 0.5 percent solution of neosynephrin hydrochloride. If there is persistent recurrence of aerosinusitis, a search should be made to determine the possible presence of tumors, polyps, scar tissue, or other causes of obstruction about the openings of the sinuses in the nose.

Effect of Pressure Changes on the Teeth

Toothache is one of the significant but correctible indispositions experienced by man exposed to changes in barometric pressure. The dental services at various AAF installations have made, and are continuing to make, clinical studies of this problem. As a typical example, 202, or 1.6 percent of over 12,000 subjects who engaged in flights in the decompression chamber at the Las Vegas Army Air Field Gunnery School, Las Vegas, Nevada, have reported toothache.

The altitude at which the onset of toothache occurs usually varies from 5,000 to 15,000 feet, but pain referable to a given tooth in a given individual often may show remarkable constancy in the altitude at which it first becomes manifest. The pain may or may not become more severe as altitude is increased. Descent almost invariably brings relief, the toothache often disappearing at the same altitude at which it was first observed.

Apart from the comparatively rare pain of the teeth or jaw which may be related to the possible effect of aeroembolism on the nerves supplying those regions, toothache may be due to simple changes in pressure during ascent or descent, the former being more frequent than the latter. Such changes do not affect normal teeth. Common sources of aerodontalgia are mechanically imperfect fillings, inadequately filled root canals, and pulpitis due to poor choice of filling materials. One of the most frequent sites of toothache in aircraft or in decompression chambers is a tooth in which an amalgam filling has been improperly inserted. If the amalgam was not properly consolidated and well packed into the prepared cavity, or if a heavy enough cement base was not prepared beneath the amalgam, changes in pressure may cause irritation of the underlying, sensitive, normal tooth structure.

In this type of difficulty, replacement of the faulty filling with properly inserted amalgam over an adequate cement base will almost invariably eliminate recurrence of symptoms. It is not advisable, however, to replace all amalgam fillings to which trouble at altitude appears referable. A filling deep enough to break into the pulp chamber and initiate certain tissue changes may cause symptoms during flight for a period of weeks following its insertion. As the tissue changes stabilize, however, symptoms will no longer occur. Therefore, in the case of a recently inserted filling, it is usually advisable to delay treatment by replacement for several weeks, at the end of which time such treatment no longer may be necessary. In this connection, zinc oxide eugenol as a base material under deep fillings has proven most satisfactory in preventing pain at altitude.

Untreated caries, especially those under old restorations and in which the pulp has become exposed, also may be the cause of toothache at altitude. Broad consideration of such cases suggests a division of these reactions into two categories: (1) pain caused by the reaction of vital pulps of carious teeth to the change in atmospheric pressure, and (2) pain caused by the reaction of degenerated gangrenous pulps to the change in atmospheric pressure. Proper dental treatment of these latter cases depends on the individual case; removal of the degenerated pulp, rather than extraction, often is adequate.

A less frequent cause of toothache occurring during ascent is the presence around the root of a tooth of a periapical abscess in which, concomitant with the infection, a small amount of gas has been generated. This gas, unable to escape, will expand with increasing altitude and may cause severe pain which can be relieved only by descent to a lower barometric pressure. Though such a tooth may present an externally normal appearance and the individual concerned may deny any previous symptoms on the ground, an X-ray will reveal evidence of the abscess. In one case which took place in a decompression chamber the periapical abscess ruptured at altitude and caused subsequent spreading infection which necessitated hospitalization.

The intense cold encountered at high altitude has been shown to bear no causative relationship to aerodontalgia. The lips, tongue, cheeks, and saliva, in addition to the oxygen mask, apparently offer an adequate protective barrier against the cold air.

The immediate treatment of toothache occurring during change of altitude consists simply of reversing directions: if toothache comes on during ascent or while at peak altitude, descent will bring relief; if it occurs during descent, reascent will alleviate symptoms. All flying personnel who suffer from toothache at altitude should be referred without delay to a dental officer for investigation and treatment.

In the event that examination following toothache at altitude fails to reveal dental abnormalities, aerosinusitis with referred pain should be borne in mind as a possible cause for aerodontalgia.

CHAPTER VI

PRESSURE CABINS AND THE EFFECTS OF EXPLOSIVE DECOMPRESSION

If standard demand oxygen equipment is used, the decrease in atmospheric pressure and the associated reduction in the partial pressure of oxygen is too great for human tolerance at altitudes above 40,000 feet. Some means of pressurizing the environment or the oxygen supply must be provided for the flyer who is to ascend to altitudes in excess of 40,000 feet. The most satisfactory method which has been developed is pressurization of the aircraft cabin.

Pressurization of aircraft cabins possesses the following principal advantages: (1) Flights may be made to high altitudes without the use of oxygen, or, in some aircraft, to altitudes exceeding 40,000 feet with only conventional oxygen equipment; (2) aeroembolism and gaseous distention are prevented or diminished, since the body is not exposed to extremely low barometric pressure; and (3) heating and ventilation can be controlled more satisfactorily. Pressure is especially advantageous

in bomber aircraft on long flights at high altitudes. The ability to get along without wearing an oxygen mask, in addition to contributing to the comfort of all crew members, enhances efficiency by enabling them to move more freely about the airplane.

Pressurized aircraft cabins have the following disadvantages: (1) Slightly increased bulk and weight become necessary in the structural design which will withstand pressure; (2) additional equipment must be maintained; and (3) personnel are exposed to explosive decompression which, though well tolerated at rates and under conditions now regarded as applicable to bombers, may be harmful in the event of the extremely rapid rates of decompression which might apply to certain types of fighter aircraft.

Recommended Pressure Differentials

The difference between the pressure inside and that outside the aircraft is termed the "pressure differential" and is expressed in pounds per square inch (psi). Hence, pressure cabins are rated according to the psi pressure differential which they maintain. At the present time, the AAF employs two levels of pressure in most aircraft, namely 6.55 psi and 2.75 psi. The greater differential is used in heavy bombers and allows an 8,000-foot level of pressure in the cabin at an actual altitude of 30,000 feet, or a 10,200-foot level at an altitude of 35,000 feet. This pressure differential, when maintained, obviates the need for wearing an oxygen mask up to an altitude of 35,000 feet. However, oxygen equipment must be available for instant use in the event of a sudden loss of pressure differential due to the penetration of the cabin by enemy gunfire.

The differential of 2.75 psi has been recommended for all fighter aircraft, and for certain other types of aircraft (photo reconnaissance and bomber) when enemy action is likely to be encountered. Such a differential does not eliminate the necessity for using oxygen at high altitudes, but it increases cabin pressure to a level at which the incidence of aeroembolism is very low. In aircraft capable of flight at altitudes of from 40,000 to 50,000 feet, limited cabin pressurization is required to prevent anoxia when the conventional demand-type oxygen system is used; a differential of as low as 1.0 to 1.5 psi averts anoxia in this range of altitude. Since, under these circumstances, pressure breathing equipment would be necessary if the pressure differential were lost, such equipment should be available on all flights to altitudes above 40,000 feet. It may be used as ordinary demand oxygen equipment, however, as long as pressure is maintained within the cabin.

The maximum desirable pressure altitude to be maintained within the cabin varies with certain physiological considerations, among which the employment of oxygen equipment is a leading factor. Pressurization requirements for normal flight are as follows:

1. 30,000-foot cabin maximum for cruise at any altitude, if supplementary oxygen is used continuously; this requirement keeps the cabin altitude below that at which symptomatic aeroembolism usually occurs. A 25,000-foot cabin maximum is advised for troop-carrier aircraft, in view of the larger number of passengers.

2. 10,000-foot cabin maximum, if no supplementary oxygen is breathed for a period of up to two hours.

3. 8,000-foot cabin maximum, if no supplementary oxygen is breathed for a period of up to four hours.

4. 5,000-foot cabin maximum, if no supplementary oxygen is breathed for periods in excess of four hours; a cabin pressure altitude corresponding to 5,000 feet is also the maximum consistent with good night vision, unless oxygen equipment is used.

5. Ground level cabin maximum, desirable for passenger aircraft; the cabin pressure should be the equivalent of the ambient pressure at the airport of destination.

In the regulation of cabin pressure the rate of pressure reduction should not be greater than one psi per second. The rate of pressure increase should not exceed one psi per minute in bomber or fighter aircraft, or 0.15 psi per minute (corresponding to a descent of 300 feet per minute) in passenger aircraft.

There are three types of pressure cabin control:

1. Isobaric control, in which the cabin is maintained at a constant pressure altitude (for example 8,000 feet) for varying flight levels.

2. Differential control, fixed by the structural strength of the cabin, maintains pressure differentials of 6.55 psi for heavy bombers and, usually, 2.75 psi for fighter aircraft. Isobaric control is utilized until the aircraft attains a flight altitude at which the difference between the pressures inside and outside the cabin is equal to the maximal differential pressure tolerated by the cabin structures. Differential control is employed at altitudes in excess of this "limiting" altitude.

3. Pressure ratio control, in which the cabin pressure is maintained at a constant ratio with the outside barometric pressure (actual flight altitude). This relationship is usually determined by the compression ratio of the cabin compressors.

Cabin pressurization is achieved by mechanical compressors designed and controlled to supply a constant mass of air to the cabin. The compressors are driven by gears from the main power plant, or by turbosuperchargers connected with the engine. The former method offers better control of cabin pressure, independent of power output by the airplane engine, but it involves greater weight for a given capacity requirement. The latter method requires less weight, but entails greater power loss to the engine with large ventilation requirements.

Temperature Control and Ventilation

Consideration of and adherence to certain general principles must precede adequate control of temperature and humidity in pressure cabins. In establishing requirements for such control a distinction first must be made on the basis of temperature range. For dry bulb temperatures below 65°F, comfort of flying personnel is primarily a function of the dry bulb temperature itself

TABLE 5

COLD TOLERANCES

Insulation of Clothing in Clo's	*1-hr flight*	*3-hr flight*	*6-hr or longer flight*	*Sweat Point*
1	35°F	60°F	65°F	70°F
2	10°F	40°F	50°F	58°F
3	—15°F	20°F	35°F	45°F
4	—40°F	0°F	20°F	32°F

One clo is defined as the insulation provided by class A uniform. Adequate protection of hands and feet is presumed. Temperatures given for the 6-hour flight are considered the optimum. Sweat point temperatures are critical values above which active perspiration is likely to begin.

and the insulating value of the clothing worn by the flyer. For dry bulb temperatures above 65°F, the wet bulb temperature (relative humidity) becomes a factor in evaluating requirements for comfort. Wet bulb temperature increases in importance at dry bulb temperature levels above 80°F. The limit of heat tolerance is found at approximately 99°F, wet bulb, irrespective of the dry bulb reading.

During flight, the dry bulb temperature should be maintained at a sufficiently low level to prevent crew members from perspiring. In this regard, the insulating value of operational clothing also must be taken into account. Prevention of perspiration is especially important in pressurized cargo aircraft, in which the presence of a large number of passengers may lead to fogging of observation windows. Table 5 summarizes the minimum cabin temperatures permissible for safe operation in relation to duration of flight and insulating value of clothing.

In desert or tropical areas, consideration must be given to the heat tolerance of flying personnel on the ground before flight and at low altitudes in flight. Table 6 outlines heat tolerances under these conditions for a flyer in a semiactive state (such as preflight check of airplane) who is wearing clothing with an insulating value of slightly less than one clo (summer flying suit).

Uniformity of temperature throughout the pressurized compartment is an important requirement, especially in aircraft utilized for the evacuation of litter patients. The temperature gradients from floor to ceiling and from front to rear of the cabin should not exceed 5°F. If warm air is distributed from ceiling to floor, as in the C-54, jet-type anemostats or directional ducts should be used to insure proper mixing of hot and cold air. Direct blasts of ventilated air on the cabin occupants should be avoided. When the temperature of the incoming air is greater than 100°F, a blast of hot, dry air causes great discomfort, especially about the eyes, face, and other exposed parts of the body. Air movement in the atmosphere immediately surrounding crew or passenger positions should not exceed 150 feet per minute.

Cabin ventilation requirements assume great importance in pressurized aircraft of cargo type, in which a large number of cabin occupants creates special problems. Assuming a cabin pressure equivalent to an altitude of 8,000 feet, the required minimum for removal of carbon dioxide, of two cubic feet of outside air per minute per passenger, is not difficult to achieve. The same may be said of the requirement for carbon monoxide, which must be limited to less than 0.005 percent by volume. Removal of objectionable odors, on the other hand, constitutes a difficult problem, especially in aircraft carrying litter patients. Factors which must be in-

TABLE 6

HEAT TOLERANCES

Relative Humidity	*Comfortably Warm*		*Tolerable*		*Extremely Difficult*
	4 hr	*1 hr*	*4 hr*	*½ hr*	*½ hr*
10%	90F (58)	97F (62)	118F (73)	134F (82)	160F (100)
50%	82F (68)	87F (73)	100F (84)	107F (90)	118F (99)
90%	76F (74)	81F (79)	91F (96)	96F (95)	103F (100)

Wet bulb temperatures are in parentheses. Temperatures are ground level tolerance for a flyer in semiactive state wearing clothing with an insulating value of 1 clo. The 4-hour tolerable temperatures are relatively safe for heavy work. The ½-hour tolerable temperatures may be considered extremely difficult for heavy work.

cluded in considering the problem of odors are space available per passenger, air temperature, humidity, the presence of tobacco smoke, and the severity and types of litter cases.

In order to aid in reducing odors without resort to mechanical means, the cabin temperature should be maintained at the lowest level compatible with the type and insulating value of clothing worn by the occupants of the pressure compartment. In addition, outside air employed for cabin ventilation may be increased by the use of a ram. In pressurized cabins in which available fresh air is inadequate for the number of passengers, recirculation of the air through filters or cleaners may be necessary. In this case, mechanical aids in addition to the supercharger may be required. To achieve a clean air requirement of 20 cubic feet per minute per passenger which may be necessary in some instances, the volume of recirculated air would be three times that ordinarily supplied for ventilating purposes by the supercharger.

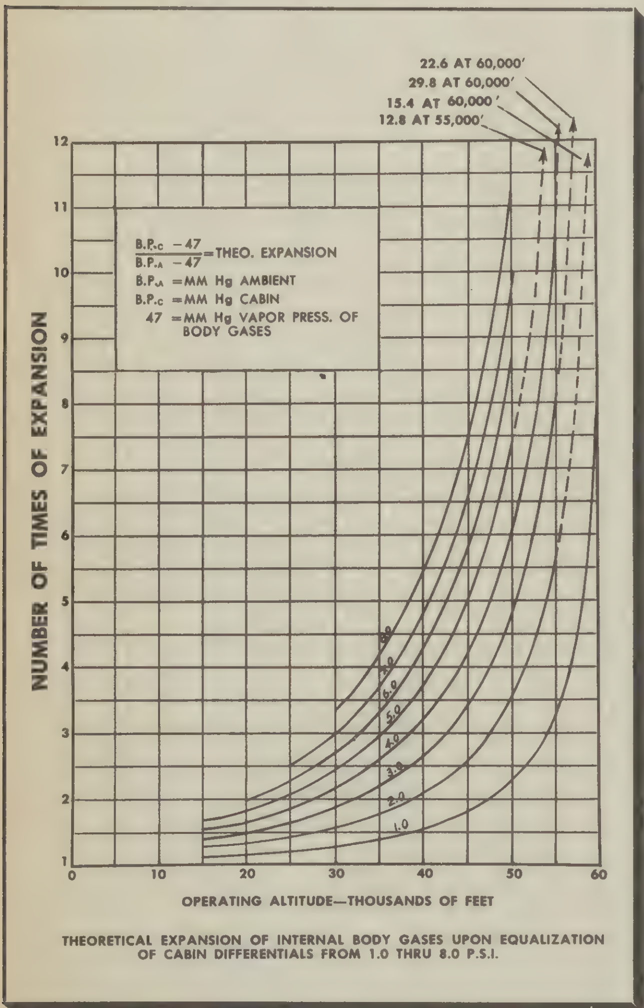


Figure 39.—Theoretical expansion of internal body gases upon equalization of cabin differentials from 1.0 through 8.0 psi.

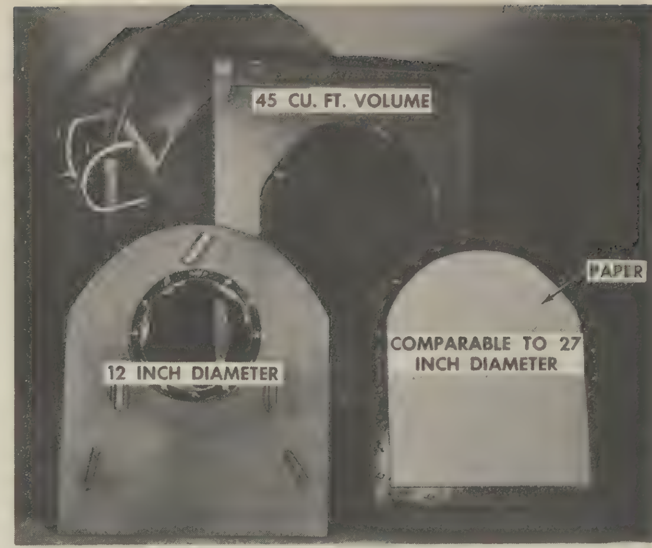


Figure 40.—Cockpit mock-up of fighter aircraft used for experiments in explosive decompression at the Aero Medical Laboratory. The photograph shows two types of opening employed.

Explosive Decompression

Explosive decompression, sudden loss of pressure differential resulting from penetration of the pressure compartment by enemy gunfire, has been considered the chief physiological hazard in connection with pressurized cabins. It is entirely possible to rupture hollow organs in the body if the expansion of gases contained within them is sufficiently great and too rapid to allow enough time for equalization of pressure. Animals have been reported killed in experiments of this type.

Investigation of the effects of rapid decompression upon man has indicated that the important factor is the rate of decompression. The rate is dependent upon the pressure differential, the size of the aperture, and the volume of the pressure compartment. Experiments involving 47 normal, healthy subjects in more than 150 rapid decompressions from a simulated altitude of 10,200 feet to one of 35,000 feet (a pressure differential of 6.55 psi) in 0.075 second (a decompression rate of 87 to 88 psi per second) produced no injurious effects, either immediate or delayed. Under these conditions, the theoretical expansion of internal gases is 3.5 times;* the decompression rate is theoretically comparable to that which would be encountered if an opening 66 inches in diameter were produced in a 1,000-cubic foot pressurized fuselage. Decompressions of this type, which

* All body gases are saturated with water vapor. The pressure of water vapor at normal body temperature is constant at 47 mm Hg. This markedly enhances the expansion of body gases at altitude, for, since it is constant, it takes up a progressively greater proportion of the total pressure as altitude increases. The theoretical expansion ratio of gases within the body is governed by the pressure differential and the altitude at which decompression occurs, and is shown in figure 39 for various pressure differentials and altitudes.

have become a routine part of the indoctrination program carried out at the Aero Medical Laboratory, Wright Field, have added many more cases to the original study, with the same results. A motion picture (WF 60-160) of the original series of experiments has been produced to demonstrate the experimental conditions, the technique, and the reactions of the subjects. Figure 40 shows the cockpit mock-up utilized in this type of experiment, with two of the openings employed.

In more recent experimentation, subjects have withstood, without injurious effects, decompressions from a simulated altitude of 8,000 feet to one of 35,000 feet (a 7.5 psi pressure differential) in 0.09 second. This involved a theoretical expansion of body gases of 3.9 times; the decompression rate was almost identical with that employed in the first series of experiments.

Other laboratory experiments on human subjects have shown that the body can withstand, without detectable harm, a loss of 2.75 psi in 0.015 second and 1.5 psi in 0.008 second at a simulated altitude of 45,000 feet. This represents a decompression rate of 125 psi per second and 170 psi per second, respectively, and a theoretical expansion of internal gases in the body of 3.2 and 2.3 times their original volume. The rate is comparable to that which would be encountered if an opening 18 inches in diameter for the former, and 27 inches in diameter for the latter, were to occur in a 45-cubic foot pressurized fighter cabin, or an opening 80 inches in diameter for the former, and 98 inches in diameter for the latter, in a 1,000-cubic foot pressurized bomber compartment.

None of the subjects lost consciousness during decompressions of these types. However, on close interrogation, many of them revealed having experienced a lightning-like period of daze. This did not prevent or cause any significant delay in the application and adjustment of an oxygen mask. No difficulty was experienced in any of the decompressions with reference to equalization of pressure between the middle ear and the environment. Of the 47 subjects utilized in the first series of experiments, only 4 complained of gastrointestinal symptoms. Three of the four had mild and one moderate abdominal pain; however, the latter had failed to reveal, prior to decompression, that he was suffering from a gastrointestinal upset with mild diarrhea. The four affected subjects experienced no discomfort in the course of two or more subsequent, identical explosive decompressions. Following explosive decompression, subjects remained at the new altitude for from 5 to 20 minutes, during which no bends or other symptoms of aeroembolism occurred. In all of the experiments herein described, the subjects experienced gushing of air from the mouth and nose. This follows the expansion of gases within the lungs, another manifestation of which can be observed in the film as a visible, transient enlargement of the chest; a similar enlargement of the abdomen also can be seen.

Present evidence indicates that the rapid decompression to which crews of bomber and cargo aircraft may be subjected constitutes no great physiological hazard, for healthy individuals tolerate well, up to 35,000 feet, the changes involved in decompression from a 6.55 psi differential at a rate of 87 to 88 psi per second and from a 7.5 psi differential at a slightly slower rate. In fighter aircraft, however, in which the cabin volume is small in relation to the opening which might be produced by enemy gunfire, explosive decompression may present greater dangers. Careful consideration must be given, therefore, to the proper choice of a pressure differential for fighter type airplanes, particularly those with the new bubble canopy. The optimal differential to be employed at altitudes above 40,000 feet can be established experimentally for fighter aircraft with this type of canopy only after controlled firing tests have been conducted to determine the maximum size of aperture which ordinarily might be expected from enemy gunfire.

Decompression in 0.005 second has been carried out to 50,000 feet employing a 1.0 psi differential (40,000-foot cabin altitude), with an opening comparable to a 27-inch diameter. The latter area is equivalent to the metallic opening in at least one new fighter ship with a bubble-type canopy. Since firing tests on scanning blisters in the B-29 have shown that a 20-mm shell causes complete disintegration of the blister, it is reasonable to expect that similar disintegration would be the result of penetration of the bubble-type canopy in fighter ships.

The decompression involving a 1.0 psi differential to 50,000 feet has been carried out on four subjects without untoward effects. Comparable to the expansion of internal gases, namely 2.3, is the decompression to 45,000 feet, with a 1.5 psi pressure differential. This was carried out on seven subjects without adverse results. In both types of decompression, the subjects were able to adequately adjust pressure breathing equipment without delay, and immediately thereafter to carry out a test involving the removal of 34 thumb nuts from the structure of the mock-up in which they were seated. These tests showed the subjects to be alert and in full possession of faculties and skills immediately following the decompression. The subjects remained at altitude for approximately five minutes after the decompression.

The subjective sensations in these experiments indicate that the upper limit of safety is being approached. From a consideration of the average vital capacity of the lungs and the amount of air normally found in them, it seems feasible to expect that the volume may be expanded two-fold before any sensations would be felt, no matter how rapid the decompression and accompanying gas expansion. Since a 2.3 expansion at very rapid rates seems to approach upper limits, it has been recommended that an override control be developed for the fighter cabin to lower the pressure from 2.75 psi to one that will not allow more than a 2.3 expansion of internal gas in the event of explosive decompression.

Though the physical expansion of internal gases resulting from explosive decompression is a function only of the pressure differential and the altitude at which decompression occurs, the rate of decompression is an important factor in human tolerance to expanding internal gases. Consequently, the volume of the pressure

cabin and the size of the opening through which pressure is lost modify the maximum limits of safety for internal gas expansion. In combat areas, where there is danger of explosive decompression, the cabin pressure is reduced to a level at which the potential relative expansion of internal gases will not be greater than 2.3 times for a 50-cubic foot cabin volume.

Demand oxygen equipment, to be used in case of emergency, should be available immediately to the occupants of pressure cabins. In pressurized aircraft flying at altitudes in excess of 35,000 feet, such equipment must be of the pressure type.

CHAPTER VII

COLD AT ALTITUDE AND PRINCIPLES OF FLYING CLOTHING

Operation of high-speed and high-altitude aircraft has created unique problems with regard to temperatures encountered by airmen. Flyers are subjected not only to various climatic conditions on the ground, both tropic and arctic, but may be required to ascend to the arctic blast of the stratosphere within less than an hour. The global nature of their operations may take them from a mild climate to one of extreme cold within one day. Because of the sudden and extreme temperature changes to which flyers may be exposed, provisions must be made for their comfort and safety. A practical application of the physical and physiological principles of body temperature regulation is the necessary basis for solving the problem of protecting aviators from extremes in temperature.

The warmest temperature likely to be encountered is that inside a closed airplane grounded on a desert. On the basis of recent observations made during the month of June inside a B-17E and a B-24D at Blythe, California, one of the hottest desert areas in the world, a cabin temperature of 48.9° C (120° F, or about 12 degrees above the temperature of the ambient air) was found to be the average daily maximum. This was the average of temperatures which occurred during the middle of the afternoons. Radiation from the sun in the desert is extremely great, and often conditions on the ground in and about the airplane become unbearable. At Blythe, crew members were known to have blistered their hands on the outer surfaces of the airplanes, and once a temperature of 73.9° C (165° F) was recorded inside the tail turret of a B-17E. Maximum temperatures inside the airplane usually were reached within 20 minutes to half an hour after a landing had been made. Because heat was radiated from the airplanes at night, cabin temperatures always fell below those of the ambient air, sometimes as much as 9.4° C (15° F).

In the tropics, because of the high moisture content of the air, radiation from the sun is not as intense as it is in the desert, nor, as a rule, are air temperatures as high. The usual tropical temperature is constant and lies in the range of 27° to 32° C (80° to 90°F). However, humidities ranging up to 95 percent cause extreme discomfort from the heat.

The coldest temperature the flyer will be likely to encounter on the ground is from —45.5° to —51° C (—50° to —60°F). These temperatures occur frequently during the winter months at Ladd Field, Alaska. Under these conditions, operation and preparation of airplanes for flight are extremely difficult, and a serious handicap is imposed on air crews who have to use their hands to perform delicate operations.

In the tropics, the ground temperature may be 35° C (95° F) while the temperature at 30,000 feet approximates —40°C (—40° F). In desert regions it is possible to find a temperature of 50° C (122° F) at ground level and —65° C (—85° F) at high altitude. It is also possible to go from an area with a ground temperature of 50° C (122° F) to a region with a ground temperature of —45.5° C (—50° F)—for example, a flight from Moffet Field, California, to Ladd Field, Alaska. Because of these great differences in temperature, thermal protection of the flyer is a complex problem.

Since it is not possible to provide flying clothing which is effective in all temperatures, it is necessary for flying personnel to understand the relation of clothing to the effects of heat and cold on the body and to the conservation and dissipation of body heat. Thus they will be able to select and care for clothing wisely and meet operating conditions effectively.

Heat Regulation

HEAT GAINS BY THE BODY.—There are two sources of heat available to the body: heat from outside sources, such as radiation from hot objects or the sun; and heat produced within the body by metabolic processes. In metabolism, which is the most important and effective source of body heat, the tissues of the body convert food into kinetic, electrical, and thermal energy or heat. The factors influencing the metabolic production of body heat are particularly important in relation to thermal insulation of the body by means of clothing.

The rate of heat production of the body in a reclining and fully rested condition 12 to 18 hours after the last meal is 60 to 70 kilogram-calories per hour for an average-sized 25-year old man. This value is known as

the basal metabolic rate. During quiet sleep the production of heat is decreased 10 to 15 percent. This decrease is one of the reasons that additional protection against cold is required during sleep.

The slight amount of exertion required to maintain the body in a sitting position increases the production of heat 10 to 20 percent above the basal rate; for an average-sized 25-year old man, the rate is increased from 65 to 80 calories per hour. The amount of effort required to pilot a plane increases the basal rate 50 percent. For an average-sized pilot, the heat output is increased from 65 to 100 calories per hour. Moderate exercise, such as walking, may raise the rate of heat production two to three times the basal rate, and extremely hard work may increase it 10 to 15 times.

Shivering is a form of exercise consisting of involuntary contraction and relaxation of certain groups of muscles in the body and may increase metabolism two to four times the basal rate. Consequently, shivering is one of the most effective mechanisms which the body possesses for increasing heat production and for maintaining a constant body temperature in cold environmental conditions.

Some heat may be gained by the ingestion of food or drink which is at a higher temperature than the body, as well as by radiation from hot objects outside the body. The body may gain heat equal to two or three times the basal rate when it is exposed to the sun's rays on a hot summer day. Under ordinary circumstances, the amount of heat gained by these methods is of minor importance as compared with that gained by increasing the metabolic rate. On the other hand, within an hour after food has been eaten, when digestion is under way, the production of heat begins to increase; it may reach a maximum of 10 to 30 percent above the basal value and is maintained at this level for several hours.

HEAT LOSS FROM THE BODY.—If the heat constantly being produced by the body were not dissipated by some means, the body temperature would steadily increase. The body is approximately 65 percent water; consequently, it has a large heat capacity and a relatively high specific heat of 0.83 kilogram-calories per degree centigrade. Thus, the body temperature of an individual weighing 80 kilograms (175 pounds) and producing heat at the rate of 80 kilogram-calories per hour would increase 0.83° C (1.5° F) in an hour if the body were not losing any heat at all. If heat were produced as fast as it was lost, there would be no change in body temperature. On the other hand, if heat were lost twice as fast as it was produced, the body temperature would decrease 0.83° C (1.5° F) for the first hour. The same decrease in temperature would not occur during the second hour but would be somewhat less, or about 0.7° C (1.3° F), since the cooling of an object is not directly proportional to time. This fact also is true in regard to increases in temperature.

There are four means by which the body loses heat at the skin surface: conduction, convection, radiation, and evaporation. A fifth method of heat loss is provided by the warming of inspired air.

Heat loss from the body by conduction passes through two conducting materials: the fibers or threads of the clothing, and the air trapped between the layers of the clothing and in the spaces between the threads of the cloth. Since the fibers or threads are not continuous from the body to the outside, almost all of the heat loss by conduction is by air conduction. Air is one of the least heat-conducting of all substances and hence affords excellent insulation. Flannel, for example, offers only one-half the insulating protection of a corresponding layer of air.

Heat lost by convection involves the movement of air. As the air at a heated surface becomes warm, the density of the air becomes less and the warm air moves upward over the heated surface, allowing cold air to move in and take on heat. In this manner, considerable heat can be carried away from a surface which is at a higher temperature than the surrounding air. The principal insulating effect of clothing is to prevent this convective movement of air. It is seen that the thicker the clothing, the thicker is the layer of immobilized air. It is also on this principle that pile fabrics are effective. Convective losses include the effect of wind or strong air movement. The faster the air moves over a heated surface, the more heat is carried away from that surface.

Loss of heat by radiation is dependent upon body size, skin temperature, and the temperature of the surrounding surfaces. It is not dependent upon the temperature of the air between the body and the surfaces of surrounding objects, as radiant heat is part of the spectrum of radiant energy occurring in the infrared region. Heat losses by radiation are important in aircraft because the temperature of the fuselage may approximate the outside temperature and considerable body heat may be lost, even though the cabin air is heated. For this reason, fabrics which inhibit radiation are important in the design of clothing. Conversely, if the surrounding objects are above the body temperature, clothing decreases the rate at which the body absorbs heat by radiation.

The body constantly is losing water from the surface of the skin by diffusion through the epidermis and from the lungs. This type of water loss is fairly constant under a wide variety of environmental and physiologic conditions. It is called *insensible perspiration* and is entirely independent of the sweat glands. Loss of water by activity of the sweat glands is called *sensible perspiration* or sweating. With every gram of water evaporated from the body, 535 calories of heat are lost. The water loss of the body by insensible perspiration from the skin surface and lungs for an average-sized individual is, on the average, 30 grams per hour, which represents 16 kilogram-calories of heat loss per hour when it evaporates. The water loss from the lungs is represented by the difference of water content in the inspired air and expired air. Air when it is inspired may have very little water content, but upon being expired, it is very close to saturation. Except when an individual is asleep, water

also is being evaporated constantly from the surfaces of the eyes. Since this water is being evaporated from a body surface, appreciable amounts of body heat are dissipated. An important result is that goggles become frosted if they are not properly ventilated or heated.

The rate at which evaporation occurs depends upon relative humidity, temperature, air movement, and the area of the evaporating surface. The rate of evaporation is less on a humid day (relative humidity 80 to 90 percent) than on a dry day (relative humidity 20 to 30 percent). The rate of evaporation increases as either the temperature or movement of air increases. A large surface allows more evaporation than does a small one. The body makes use of this fact by increasing the surface area over which sweating occurs as more heat loss from the body is necessary. The armpits, forehead, and palms of the hands begin to sweat first, and as more heat loss is demanded because of increased humidity, air temperature, or metabolic heat production, the perspiring areas extend more and more over the body. The heat loss by sensible perspiration may represent no loss when the body is cool and the sweat glands inactive, or it may represent as much as 95 to 98 percent of the total loss of body heat in a hot environment with a low relative humidity.

Loss of body heat brought about by the warming of inspired air is dependent on the temperature of the air when it is inhaled. Exhaled air has a temperature only a few degrees less than that of the body. For an average-sized individual breathing normally in an ambient temperature of 20° C (68° F), 1.6 calories of heat are lost; this amount is equal to 2.0 percent of the total loss of heat. If a person is breathing air at a temperature of —40° C (—40° F), 10.4 calories are lost; this amount is equal to 16.1 percent of the total loss. If the temperature of the air is higher than that of the body, there is no loss of heat by this means, and it is possible that a small amount of heat might be gained by the body.

Table 7 summarizes the various ways of heat loss from an individual comfortably clothed and producing 80 kilogram-calories per hour. The air temperature is 20° C (70° F) with a relative humidity of 50 percent, and the air movement is 10 cm per second. Only approximate values are given.

TABLE 7

MECHANISM OF BODY HEAT LOSS

Mechanism	*Loss in Calories per Hour*	*Percent Loss*
Conduction	28.8	36
Radiation	24.0	30
Convection	8.0	10
Insensible Perspiration	17.6	22
Skin	9.6	12
Lungs	8.0	10
Warming of Inhaled Air	1.6	2
TOTAL	80.0	100

REGULATION OF HEAT LOSS BY THE BODY.—The body can carry on its various vital functions efficiently only in the rather narrow temperature range of 36° to 38° C (96.8° to 100.4° F), the optimum temperature being 37° C (98.6° F). Through the use of certain physiological mechanisms, this optimum temperature is maintained relatively constant in a wide variety of environmental conditions. To maintain such a constant body temperature, the rate of heat production and the rate of heat loss must be closely regulated and balanced. The heat regulatory center in the brain is very sensitive to variations in deep body temperature and thereby controls the various physiological mechanisms which produce alterations in the gain and loss of heat by the body.

From a practical viewpoint, the regulation of heat by the body over a wide range of temperatures can be divided into two major zones. In the zone of higher temperatures, evaporation (principally by means of sensible perspiration), vasodilatation, and the large thermal heat capacity of the body are the principal regulatory mechanism. As the skin temperature of an individual increases, either because of a higher ambient temperature or an increased metabolic rate, the sweat glands become active, thus causing more cooling by increased evaporation. At the same time, vasodilatation* occurs; the capillaries and arterioles in the dermis dilate, increasing the peripheral circulation. As a consequence, a greater volume of blood is brought near the surface of the skin in a given period of time and there is a more rapid loss of deep body heat, since most of the heat is transferred from the interior of the body to the skin by the circulation of the blood. Because of its large heat capacity, the body absorbs or gives off moderate amounts of heat before any critical change in body temperature occurs. A loss or gain of 66.4 kilogram-calories is necessary for a change of 1 degree in the over-all body temperature.

In the zones of lower temperature, the shivering reflex, vasoconstriction, and the large thermal capacity of the body are the principal temperature regulating devices. If the average skin temperature falls much below 30° to 31° C (86° to 88° F), involuntary shivering begins, with the result that the rate of heat production is increased. As the temperature of the skin decreases, vasoconstriction occurs, causing the capillaries and arterioles to shrink in size. The amount of blood passing through the outer tissues of the body is greatly reduced, so that less body heat is lost; this reduction in peripheral circulation causes the skin of the body to be-

*Vasodilatation is evidenced in persons who are very warm or who are expending a great amount of energy by the redness of their faces and hands. Blushing is a form of sudden vasodilatation as the result of an emotional disturbance or stimulus.

come an effective heat insulator. "Gooseflesh," sometimes occurring just before and during shivering, often accompanies a high degree of vasoconstriction. Laboratory results have shown that complete vasoconstriction, in its ability to conserve heat, is equivalent to wearing light woolen underwear.

The dividing line between the two temperature zones is the critical ambient temperature at which heat regulation by sensible perspiration begins. For the nude body, this critical ambient temperature lies between 30° and 32°C (86° and 89°F), and it becomes lower according to the amount of clothing worn. When olive drab shirt and trousers are worn, the critical temperature lies at 25°C (77°F), assuming that the subject is in a sitting-resting position, as he might be inside an airplane. It is obvious that exercise or more clothing will lower the critical point.

It is extremely important for the flyer who must wear flying clothing inside a warm airplane for some time before taking off to know roughly the critical temperatures at which sweating begins and under what environmental conditions he should reduce exercise to a minimum. When one must fly from a warm environment to a cold environment, perspiration-soaked clothing is very dangerous, as the insulating qualities of the clothing are greatly reduced.

The extremities, particularly the hands, play an important part in the regulation of body temperature. Because the hands have a surface area which is proportionately greater per unit volume of tissue than that of the other external structures of the body, and because of their proportionately greater amount of circulation, they are responsible for an appreciable part of the dissipation of metabolic heat. The hand temperatures also exert considerable effect upon the nervous system (vasomotor system); this effect is manifested in vasoconstriction or vasodilatation. If the average skin temperature of the hands falls much below 28° or 29°C (82° or 84°F), generalized vasoconstriction occurs and peripheral circulation is reduced, even though the average skin temperature of the body remains at 33°C (91°F); this reduced peripheral circulation decreases the loss of body heat. Conversely, if the temperature of the hands is much above 28° or 29°C, generalized vasodilatation occurs, accompanied by increased peripheral circulation which results in increased loss of body heat.

The Protective Action of Clothing

The physiological protective devices for the regulation of heat loss and gain are effective in maintaining a constant body temperature for the nude body in an ambient temperature range of 20° to 40°C (68° to 104°F), if the relative humidity is less than 100 percent and the air movement is not excessive. In extremely low ambient temperatures, the physiological devices are not adequate and some means of external protection, such as thermal insulation in the form of clothing, must be provided to conserve body heat.

In cold environments the essential problem is to conserve body heat as much as possible. Under such conditions the secretion of sweat is stopped entirely, and the loss of heat by evaporation is confined to the moisture which diffuses through the skin and that evaporated from the lungs. Vasoconstriction occurs, and peripheral circulation is greatly decreased. By covering the body with clothing, a thermal resistance (insulation) is interposed in the gradient from the skin temperature to the environmental or ambient temperature. Clothing also may serve to a definite advantage in high ambient temperatures, as it protects the body from absorption of radiant heat.

The comfort of an individual in relation to the temperature of the environment is dependent on many variables. In the final analysis, however, comfort is dependent largely upon skin temperature. The optimal average skin temperature for comfort is 33°C (91°F). Such an average skin temperature may be maintained in cold environments if the clothing is chosen properly in relation to the degree of activity. The regulation of heat loss and gain to maintain a constant body temperature can be attained within a limited temperature range by adjustments of peripheral circulation and evaporation. In the extremes of this range, however, maximum comfort is precluded by the nature and degree of the physiological adjustment.

If a temperature equilibrium is to be obtained without significant physiological adjustments, three factors are concerned in the balance of skin temperature for optimum comfort: the rate of heat production, the ambient temperature, and the insulating value of the clothing. By standardizing these three factors, a unit of thermal insulation of clothing is defined. This unit is called *clo* and is the amount of thermal insulation (clothing) necessary to maintain an average skin temperature of 33°C (91°F) in an air temperature of 21°C (70°F) when the individual is sitting quietly (metabolic rate equal to 50 calories per square meter per hour). The relative humidity is held constant at 50 percent and the air movement at 10 cm per second. Under such conditions 24 percent of the metabolic heat production is lost in evaporative cooling. Thus, 76 percent of the metabolic heat, or 38 calories per square meter per hour, passes from the skin surface through the clothing to the outside. The insulation is defined in metric units by

$$\frac{33°\text{C} - 21°\text{C}}{38\text{k cal}\times\text{hr}\times\text{m}^2} \text{ or } .32 \frac{\text{C}}{\text{k cal}\times\text{hr}\times\text{m}^2}.$$

It has been found in the laboratory that

$$.14 \frac{\text{C}}{\text{k cal}\times\text{hr}\times\text{m}^2}$$

of the insulation is provided by still air at the surface of the clothing. The insulation of the clothing alone, then, is .32-.14 or

$$.18 \frac{\text{C}}{\text{k cal}\times\text{hr}\times\text{m}^2};$$

this is equal to one clo, or the amount of insulation provided by cotton underwear, wool shirt, wool trousers, and appropriate footgear.

It is possible to predict the amount of clothing necessary for any given ambient temperature. For example, a pilot sitting quietly at —30°C (—22°F) will require enough clothing to provide an insulation of

$$\frac{\dfrac{33°C - (-30°C)}{50 \times .76} - .14}{.18} = \frac{\dfrac{63}{38} - .14}{.18} = \frac{1.52}{.18} = 8.4 \text{ clo}$$

to be comfortable. This amount of clothing is represented by two complete sets of heavy shearlings.

A more active crew member, such as a waist gunner, requires less clothing when he is exposed to the same ambient temperature, as he is producing more metabolic heat. Assuming that a waist gunner is producing metabolic heat at the rate of 100 calories per square meter per hour, the insulation he will need at —30°C (—22°F) is

$$\frac{\dfrac{33°C-(-30°C)}{100K \text{ cal/hr/m2} \times .76} - .14}{.18} = \frac{\dfrac{63°C}{76} - .14}{.18} = \frac{.83 - .14}{.18} = \frac{.69}{.18} = 3.8 \text{ clo.}$$

This is the amount of insulation provided by a suit of medium weight shearling. The graph in figure 41 shows the thermal insulation necessary at a given ambient temperature with different levels of metabolic heat production.

The amount of thermal insulation provided by clothing is primarily a function of its thickness. The insulation is fundamentally due to the low conductance of the air which is more or less immobilized in the clothing, so that convection currents are inhibited. A layer of air 1

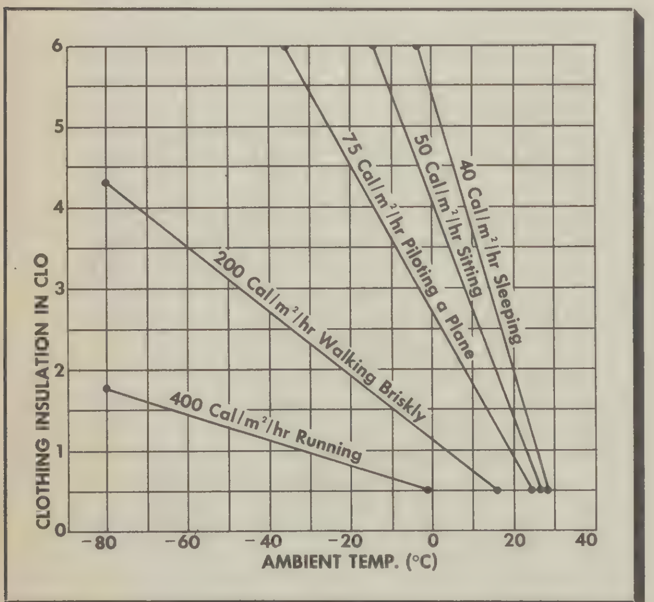


Figure 41.—Clothing insulation necessary to maintain comfort at various ambient temperatures. Clothing insulation expressed in clo units, temperature in degrees Centigrade. Values beyond 4-1/2 clo have no practical application to clothing.

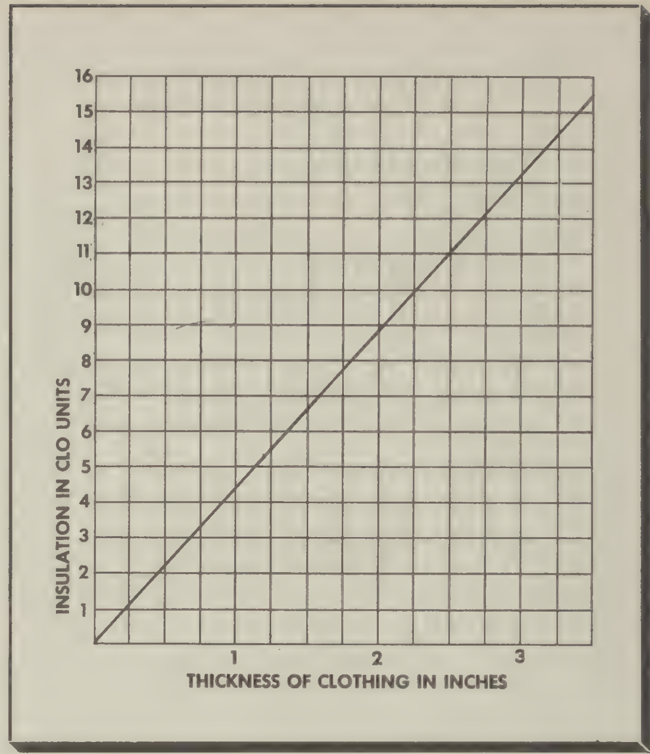


Figure 42.—Relation between thickness of clothing and clo value. Clothing thicknesses beyond 1 inch are largely theoretical.

cm thick has a conductance of 2.04 kilogram-calories per hour per square meter per degree; a layer of air 1 inch thick has a conductance of .80 kilogram-calories per hour per square meter per degree, which is equal to 6.9 clo. However, clothing 1 inch thick has an insulating value approaching 4.0 clo. The relation between the thickness of clothing and its insulating value is shown in figure 42.

Although the thermal insulation increases as the thickness of clothing increases, there is a maximum thickness which is practical if any degree of bodily agility is required. Experience has shown that this maximum thickness is 1 to 1¼ inches, which is equal to 4.0 or 5.0 clo units. Thicker clothing becomes unduly bulky and cumbersome. The maximum thickness of clothing which is practical limits the use of insulating clothing to moderately low ambient temperatures. For clothing 1¼ inches thick, the minimum temperature in which it can be used for any length of time is −10°C (14°F) for a person who is seated, −30°C (−22°F) for a person who is walking slowly, or −50°C (−58°F) for a person who is walking briskly.

It must be understood that clo is a unit of measurement for the amount of insulation necessary to keep a person comfortable, that is, with a constant skin temperature of 33°C (91°F), during exposure to a given ambient temperature. As the body has a considerable capacity for heat, an appreciable quantity of heat can be lost before there is very much change in the average

skin temperature. Approximately 200 kilogram-calories of heat can be lost from the body of an average-sized individual, and the average skin temperature can drop 5°F or more before he becomes intolerably cold. The rate at which body heat is lost depends on (1) the amount of insulation, (2) the heat capacity of the body, (3) the rate of metabolic heat production, (4) the ambient temperature, and (5) the velocity of movement.

Convective heat losses depend upon the velocity of air movement, among other factors. Although the ambient temperature remains constant, the cooling effect of wind of a given velocity may be equivalent to that of a lower ambient temperature. The temperature equilibrium of a clothed individual is reached more quickly and is lower with wind than without wind at the same ambient temperature. For example, 2 hours are required for the body to reach a temperature of 30°C (86°F) in an ambient temperature of 10°C (50°F) with a given assembly of clothing and no air movement. With wind of a given velocity under the same conditions, the temperature equilibrium of the body is lowered to 29°C (84°F) and is reached in an hour and a half. In an ambient temperature of 10°C, such an accelerated cooling effect of wind may be equivalent to an ambient temperature of 0°C (32°F). In the foregoing example it is assumed that the outer covering of the clothing permits little air movement to penetrate into the clothing. If the wind penetrates the clothing, the cooling effect of the wind is much greater. Therefore, the windbreak qualities of the outer covering of clothing are important.

If the windbreak qualities of the clothing are adequate, the accelerated cooling effect of wind is essentially due to a decrease in the thickness of the layer of warm air ordinarily found surrounding the surface of the clothing. With increasing wind velocities the thickness of this layer and hence its total insulating effect decreases. With increasing altitude the insulating value of this surface layer is increased. The graph in figure 43 shows the relationship at various altitudes between the insulation of the layer of air and wind velocity. From the graph it is seen that, at ground level, the total insulation of clothing may be altered as much as 30 percent for clothing with an insulating value of 2 clo, and 15 percent for clothing with an insulating value of 4 clo.

The rate at which the body cools, when the clothing is not adequate to maintain a constant average skin tem-

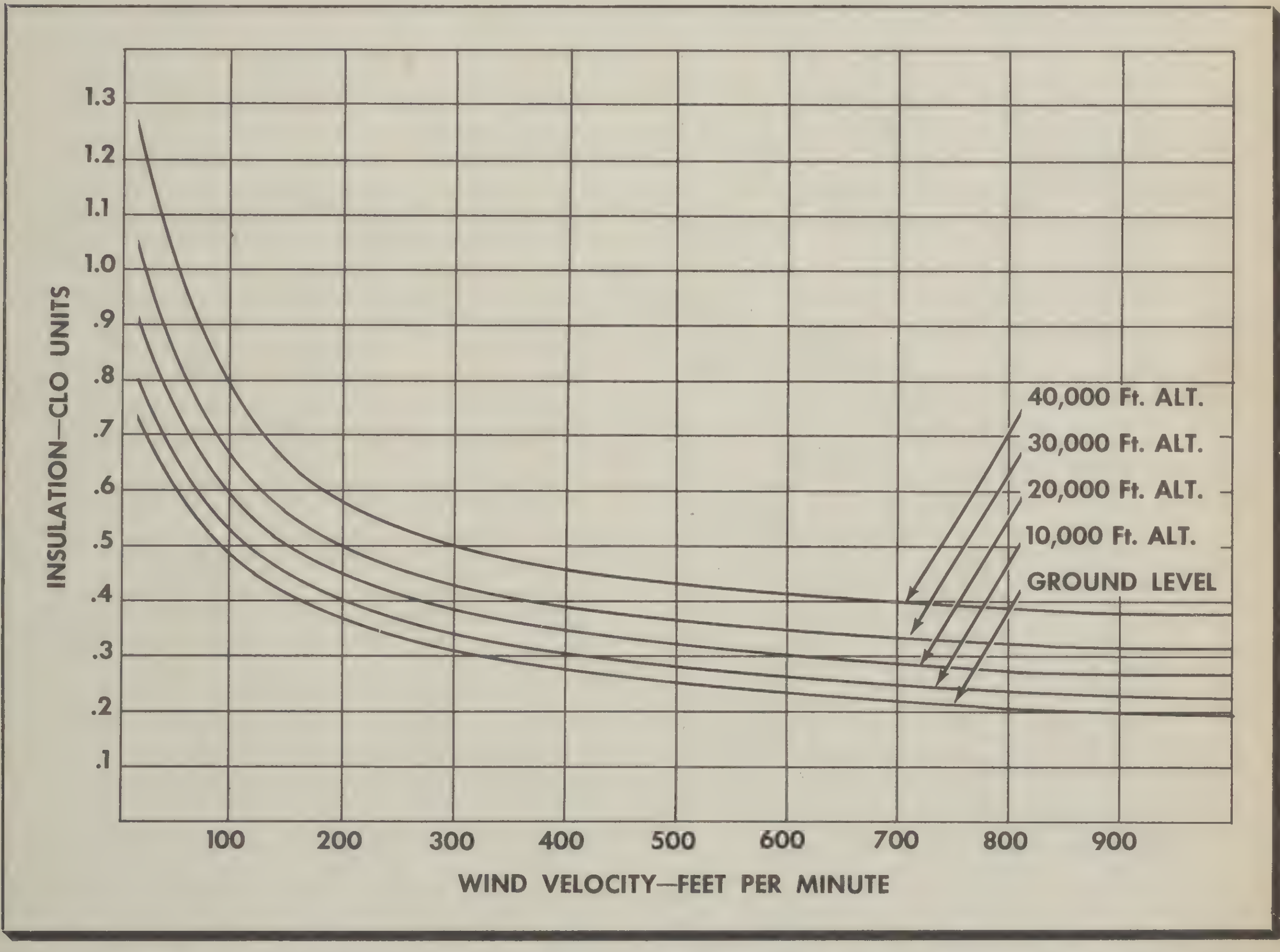


Figure 43.—Relation at various altitudes between wind velocity and insulation provided by layer of air. Insulation expressed in terms of clo value.

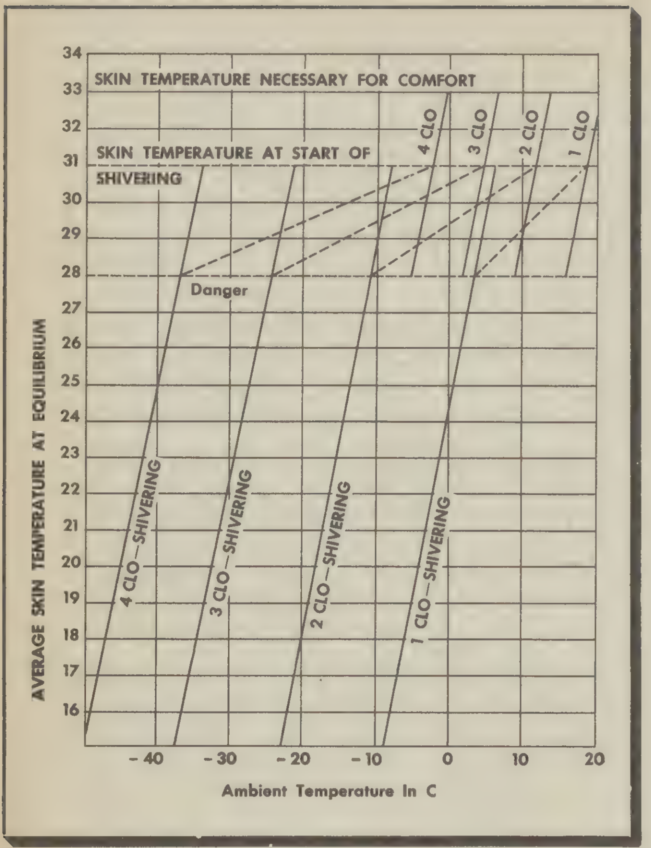


Figure 44.—Average skin temperatures at equilibrium for varying clo values and ambient temperatures. Tolerance of comparatively large decreases in the ambient temperature is due to shivering.

perature for comfort, is important if the difference between the ambient temperature for which the clothing is adequate and that for which it is insufficient is not too great. Under such conditions the time necessary to perform a mission may be of such length that no serious consequences will result. The flyer may be cold, but as long as not more than 200 calories of body heat are lost or the average skin temperature does not fall below 30°C (88°F), his ability to perform his job will not be impaired. For example, an assembly of clothing has an insulating value of 3.5 clo and so is adequate for 4° to 0°C (39° to 32°F), but the ambient temperature during exposure is —10°C (14°F). Under such conditions, the individual will be able to withstand this temperature for from 3 to 5 hours.

Figure 44 shows the relationship between the average temperature of the skin at equilibrium and the ambient temperature for several values of clo, indicating the decrease in ambient temperature which can be tolerated for a given clo value because of the increased heat production associated with shivering. For example, 4 clo will maintain an average skin temperature of 33°C (91°F) at an ambient temperature of 0°C (32°F); with shivering the ambient temperature can be decreased to —34°C (—29°F), and by allowing the average skin temperature of the body to cool to 28°C (82°F), the ambient temperature can be decreased to —37°C (—35°F). Thus, by shivering and allowing the body to cool, the effectiveness of the insulation of 4 clo has been extended to allow the ambient temperature to be decreased to —37°C (—35°F). Figure 45 shows the calculated time, in relation to the ambient temperature, for the average skin temperature to cool from 33° to 28°C (91° to 82°F) with different values of insulation.

That an individual can lose up to 200 calories of body heat or allow his average skin temperature to fall to 29° or 28°C (84° or 82°F) without deleterious results is true only when the body heat content is initially at its normal value and when there has been only one exposure to cold in a 24-hour period. A person's tolerance to cold may be reduced as much as 30 percent for some time after a prolonged exposure to cold. Decreased tolerance to cold during a second exposure within 24 hours after the first is psychological as well as physiological, and by impairing a flyer's efficiency, it may interfere with the satisfactory performance of a mission.

The foregoing discussion has been concerned with thermal insulation for the body only. The extremities, especially the hands, present special problems. Although, because of the shivering reflex and the large amount of body heat loss which is tolerable, the body can withstand ambient temperatures as low as —35°C (—31°F) when it is adequately insulated, it is impossible to provide sufficient insulation for the hands to withstand such temperatures without seriously affecting manual dexterity. It is obvious that if a thermal insulation of 4 clo, equivalent to a 1-inch thickness of insulating material, were used, manual dexterity would be greatly reduced. The thickest insulating material that can be used on the hands without decreasing manual dexterity is ¼ to ⅜ inch. This thickness is equivalent to 1 or 1½ clo. Hence, in a complete assembly of insulating clothing, the hands are the weak points and the adequacy of insulating clothing for the entire body is limited by the protection available for the hands.

Although thermal protection for the hands is a serious problem, the difficulty is somewhat mitigated by the fact that 1 clo has more insulating effect on the hands than on the body. The average skin temperature for comfort of the hands is about 4°C (7°F) lower than that of the body, or 29°C (84°F). Under similar conditions of vasodilatation the hands lose more heat than does any equivalent portion of body surface. During vasodilatation the hands lose, on the average, 60 calories per square meter per hour, while an equivalent body surface area loses 50 calories. Evaporative cooling also is somewhat greater for the hands than for the rest of the body and accounts for approximately 30 percent of their total heat loss. Thus, an insulation of 1 clo on the hands will keep them in a state of comfort at an ambient temperature of 15.6°C (60°F).

It has been found in the laboratory that the average skin temperature can become as low as 7.0°C (45°F) without any loss of dexterity, although such a low temperature will be painful. By allowing the hands to cool this much, the ambient temperature can be decreased to 0.6°C (33°F) with 1 clo insulation on the hands.

Adequate protection for the feet does not limit the use of insulating gear as markedly as does that for the hands. An insulation of 2 clo, which, due to inherent anatomical factors, is the maximum practicable clo value for standard AAF footgear, does not hamper walking ability. The hands are the principal weak points in a complete assembly of clothing. Though the feet also represent a problem, the total adequacy of insulating clothing for the entire body is limited mainly by the protection available for the hands.

ELECTRICALLY HEATED CLOTHING.—The second type of protection against cold is electrically heated clothing. The use of insulating clothing is limited by the ambient temperature, the rate of production of metabolic heat, the bulk of the insulating material, and the protection given the hands. The use of electrically heated clothing, however, is not limited by these factors, but instead by the amount of electricity available in the airplane, and by the distribution and capacity of the heating elements in the suit.

The fundamental principle of electrically heated clothing is the provision of an outside source of heat to augment metabolic heat. As a result less thermal insulation is necessary, or that which is available is made more effective. For every watt-hour of power used, 0.86 kilogram calories of heat per hour are developed. As 4½ clo provide the maximum practical insulation and keep an individual comfortable in an ambient temperature of −10°C (14°F), the amount of electrical heat, if it is 100 per cent efficient, which will have to be provided to maintain comfort at −50°C (−58°F) is 48.8 calories per hour per square meter

$$\frac{\dfrac{33°C\text{-}(-50°C)}{38 \text{ cal} + x} - .14}{.18} = 4.5.$$

This amount of heat is equivalent to 56.7 watts. However, electrically heated clothing is approximately 40 to 60 percent efficient, depending upon the air movement, the amount of thermal insulation between the skin surface and the heating elements, and the insulation be-

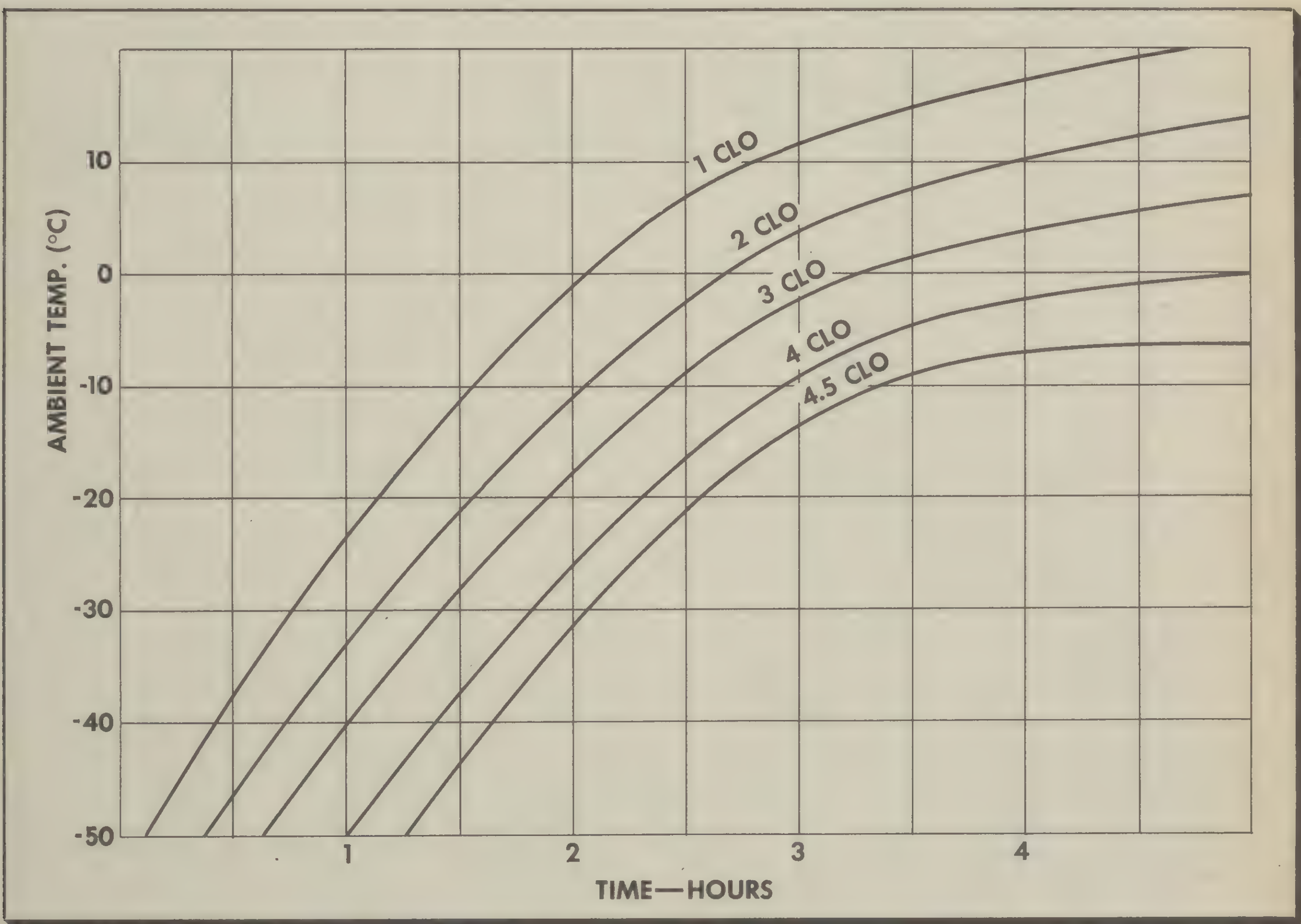


Figure 45.—Time required for the average skin temperature to cool from 32° to 28°C under different conditions of insulation and ambient temperature. This assumes an equal rate of cooling for all areas of the body surface.

Figure 46.—F-2 electrically heated flying assembly, in various stages of dress.

tween the heating elements and the outside. The less thermal resistance or insulation in the form of clothing there is between the heating elements and the skin, the more efficient is the use of electrical heat in clothing. Likewise, more thermal insulation between the heating elements and the outside increases the efficiency of electrically heated clothing.

The two electrically heated clothing assemblies in general use at the present time, the F-2 and F-3 suits, have a power consumption of 275 and 260 watts respectively. The F-2 assembly (figure 46) has an effective clo value of 2.9 with no power consumption and 7.3 with full power consumption. The heating elements are more or less uniformly distributed over the body so that for an average-sized individual (1.9 square meters, allowing for the increased surface area due to the clothing underneath the heating elements), the power consumption is 144.8 watts per square meter per hour, which is equivalent to 124.5 calories per square meter per hour. But since only an additional 45.3 calories per hour per square meter

$$\frac{\dfrac{33°C + 22°C}{38 \text{ cal} + x} - .14}{.18} = 2.9$$

are needed to make 2.9 clo equivalent to 7.3 clo, the suit is 38 percent (45.3/124.5) efficient.

The F-3 electrically heated assembly (figure 47) has an insulation of 3.6 clo without any electrical power and 8.7 clo with full power consumption, which is 136.8 watts per square meter per hour, or 117.6 calories. Since only an additional 69.5 calories per hour per square meter are needed to make 3.6 clo equivalent to 8.7 clo in protective action, the suit is 59 percent efficient.

The greater efficiency of the F-3 suit is partly the result of better distribution of the heating elements and the use of a good windbreak cloth on the outside, which decreases the penetration of air currents. The principal reason for its greater efficiency is that the bulk of the alpaca insulating material is on the outside of the heating elements.

Theoretically, electrically heated clothing is ideal for flying at high altitudes over warm climates. It is light in weight and very flexible. The hands and feet are kept more or less warm, and the heat developed can be closely controlled. There have been many problems in design and mechanical details which have been aggravated by lack of knowledge on the part of flying personnel as to how the clothing should be used. The present suits have greatly minimized these problems, but unless the clothing is used intelligently, it will not give

Figure 47.—F-3 electrically heated flying assembly, in various stages of dress.

satisfactory service. Each suit when issued is accompanied by full printed instructions for its care and use. These instructions should be followed carefully.

The first suits were wired in series so that if a break occurred anywhere, the whole circuit was affected. The wires often broke at places where they bent frequently, such as at the ankles. At places where the suit was drawn tight, such as over the knee, burns occurred. The present suits have better distribution of heat. Parallel wiring is now used so that one damaged place does not disrupt the whole circuit, and the tensile strength of the wire has been increased.

In the past, some of the boots began to smoke when the wire insulation wore thin because of frequent bending or improper care. Some of the electrically heated boot inserts developed "hot spots" because they were worn as slippers without the protection of the outer shoe; consequently, the wire insulation wore very thin. For this reason, some flyers have developed an unjustified antipathy toward the use of electrically heated clothing.

One of the chief criticisms of electrically heated clothing is that there is not sufficient protection against the severe cold if the circuit supplying power for the clothing is shot away during combat. The F-2 and F-3 suits have remedied this situation to some extent. An individual wearing the F-3 suit with its outer alpaca covering can withstand a temperature of —40°C (—40°F) with no wind for approximately an hour if the power supply has been disrupted. Under the same circumstances, a person wearing the F-2 suit can withstand the cold for approximately ½ hour.

PROPER USE OF CLOTHING.—Clothing should be kept as dry as possible. Water conducts heat approximately 25 times as fast as air, while water vapor conducts heat 2 to 3 times as fast. In addition, the heat capacity of water is approximately four times as much as that of air, while water vapor has a heat capacity of twice that of air. A large amount of heat can be lost through evaporation of any water present in the clothing.

Closely allied with the problem of dampness is that of ventilation. Unless the water vapor given off as insensible perspiration can pass through the clothing freely, it collects in the clothing and reduces insulation. If one is dressed for low temperatures and has to spend appreciable time in moderate temperatures, or if one has periods of considerable activity with a resultant increased production of body heat, sweating occurs. With subsequent decreased activity or lowered air temperature, insulation is decreased more than it normally would be if ventilation of the clothing were adequate.

The fit of the clothing has considerable influence on its insulation. If the size of a garment is too small for an individual, not only flexibility but insulation as well is decreased. The clothing will be compressed over the knees and buttocks, and over the shoulders and elbows. In these areas, insulation will be greatly decreased because of the reduced thickness of the material as well as of the air spaces, with the result that cold spots will develop. The principal disadvantage of clothing which is too large for an individual is that it may hinder his moving about. Insulation is not seriously affected, but there may be considerable heat loss because of bellows action during movement.

Adequate closures at the neck, wrists, waist, and ankles do much to increase the protective action of clothing. The function of closures is to prevent the warm air about the body from escaping and to prevent the cold, outside air from entering, such as might occur with bellows action or the penetration of wind. To be as efficient as possible, closures should be as snug as comfort allows and they should permit considerable overlapping of the clothing material. There should be no gaps at the waist between the jacket and trousers or at the ankles between the trouser legs and the shoes.

It is important that flying clothing be kept clean. Oil and grease on clothing decrease its insulation. Shearlings and alpacas tend to mat and pack down when they become dirty or oily. Dirt also hastens deterioration of fabrics so that they may rip unexpectedly under a strain and suddenly expose the flyer to severe cold at high altitude, with serious consequences.

Electrically heated clothing demands special care in its use. It should not be worn except in the plane or going from the hangar to the plane. It should not be worn while in the hangars or around the landing field for any length of time. Care should be taken not to sweat excessively while wearing electrically heated flying clothing, particularly at ground level. One may not be able to prevent sweating in hot, humid areas, but it can be decreased appreciably by limiting activity to that which is absolutely necessary. Electrically heated clothing should not be allowed to lie around or be wadded up. It always should be hung up when not in use. After putting on an electrically heated assembly, the flyer should check all electrical connections, such as those between the gloves and jacket, between the jacket and trousers, and between the trousers and shoe inserts, to insure that they have been properly made. The Personal Equipment Officer of the flyer wearing the assembly should see that all electrical contacts as well as the electrical circuits of the suit are checked frequently to insure that they are in order. Such precautions are imperative to prevent breakdown of the clothing while it is in use.

The physiological effects of insufficient oxygen already have been discussed in detail, but their relation to the problem of clothing should be emphasized as well. Oxygen consumption increases with cold through the medium of increased muscular activity (shivering reflex, etc) induced by low skin temperatures. Hence, adequate clothing provides an indirect method of aiding in the conservation of the oxygen supply.

Underwear.—The importance of heavy woolen underwear as a fundamental garment for use with insulating clothing in very low temperatures must be emphasized. Light weight cotton or woolen underwear is best for use with electrically heated clothing.

Footgear.—Keeping the feet warm is difficult because of their reduced blood supply. The problem is especially

difficult when one is standing or sitting still for long periods. Dampness, either from perspiration or from outside sources, contributes to cold feet and may lead to frostbite. Woolen socks should always be worn and they should be thoroughly dry before they are put on.

Adaptations of the Eskimo mukluk may prove to be effective in dry cold. The mukluk has several layers which can be taken apart easily for drying. These layers rub together and produce heat by friction while the wearer is walking. Although the feet eventually become cold if inactive, they are warmed by walking or foot exercises. The mukluk is not waterproof and should not be worn in melting snow.

Felt boots with leather soles have been used successfully with heavy wool socks. However, they are not adequate in wet cold, as moisture can penetrate very easily. The felt boot is quite satisfactory for use with electrically heated foot inserts. First a light wool sock is put on, then the electrically heated insert. Over these a heavy wool sock is pulled on, followed by the felt boot.

The best all-around footgear available at the present time is the leather, sheepskin-lined A-6 boot. This boot can be used with electrically heated clothing or over a regular shoe. It is partially waterproof and can be used in melting snow as long as the slush does not come higher than the rubber part of the boot.

The problem of an escape shoe for use after having to bail out or make a forced landing has not been solved satisfactorily for all conditions likely to be encountered. The felt boot used with electrically heated clothing is not adequate because, in addition to becoming soaked easily, it is not sufficiently durable. The A-6 shearling boot is unsatisfactory because, in addition to its lack of wearing quality, it is heavy and cumbersome. Reports from the field indicate that the best shoe for walking is the standard, heavy leather G. I. shoe. This shoe wears well under most conditions and does not allow water to penetrate readily. An electrically heated oversock is now being developed, to be worn over the G. I. shoe and under the A-6 boot. If it is necessary to bail out or make a forced landing, the A-6 boot and the heated insole can be discarded and the flyer still will have a satisfactory shoe for walking.

Gloves.—Adequate protection for the hands has been particularly troublesome. As has been pointed out, it is impossible to provide insulating protection for the hands at temperatures much below 0°C (32°F) for any length of time if manual dexterity is to be maintained. Electrically heated gloves are the only means of thermal protection for the hands at low temperatures when dexterity is necessary.

The size of gloves has a direct effect on their insulating value as well as on the individual's manual dexterity. If the glove is too small, it is compressed at certain pressure points, thus reducing the thickness of the insulating material. The insulating qualities of gloves which are too large are not materially altered, but dexterity may be reduced. Wrong sizing of gloves has been responsible for a large number of frostbite cases; flyers wearing gloves of improper size have found it necessary to remove them when any degree of manual dexterity was required during flight at high altitude, and, as a result, often have suffered frostbite of the fingers.

By practicing his required manual operations while wearing gloves, an individual can develop the same dexterity when gloved as he possesses when barehanded. This is very important for flyers, as it will render unnecessary the removal of their gloves except in unusual instances. If gloves are kept on at all times during flight, the hands are not given the opportunity to chill rapidly, and they do not become painfully cold as quickly as when the gloves have been removed for short periods.

A thin rayon glove insert has been recommended to be worn next to the hands under all gloves. If, in exceptional instances, the outer glove must be removed, the rayon insert still affords some protection against frostbite and does not interfere with the agility and finer movements of the fingers. It is emphasized again that flyers should become thoroughly accustomed to wearing gloves while performing any operation which may be required of them during flight, so that the gloves need not be removed at high altitudes.

The A-3 or summer flying glove does not offer much thermal protection. It is adequate for temperatures as low as 4.4°C (40°F). The A-11 or intermediate glove is adequate for temperatures as low as −5°C (23°F). There is no loss of manual dexterity when these gloves are worn if they are properly fitted. The shearling-lined A-9 mitten is adequate for temperatures as low as −10°C (14°F), but causes an appreciable loss of manual dexterity. When further protection is necessary, electrically heated gloves must be used. These gloves are satisfactory for temperatures down to −50°C (−58°F).

Facial Coverage.—Oxygen masks are worn on all high altitude missions. At the present time masks are being improved to provide better coverage and to prevent their freezing to the face. The latest proposed mask, helmet, and goggles assembly provides practically complete facial coverage and protection.

Various devices have been proposed to protect the face from extreme temperatures on the ground, although none of the measures has proved to be entirely successful. Eventually all of these devices freeze to the face when hoarfrost from the breath collects to a sufficient extent. A surprising amount of ice formed from moisture in the breath accumulates in temperatures below −35°C (−30°F).

The best protection is provided by a hood which extends forward beyond the face a sufficient distance to create a small space of dead air around the face. Fur around the hood (preferably wolverine, since it sheds hoarfrost easily) is a great protection. A woolen scarf is of some benefit in shielding the face.

Material.—The insulation, weight, and texture of the outer garments depend upon the conditions for which they have been designed. Clothing for the extreme tem-

Figure 48.—Quilted down clothing assembly. This has been issued only in limited quantities.

Figure 49.—Standard shearling clothing assembly. Shearling is being replaced by alpaca-wool.

peratures of arctic winters and for high altitudes must, of course, have as much thermal insulation as possible. For insulating clothing, it has been pointed out that the maximum insulation practical is 4.5 clo and for electrically heated clothing, 8.7 clo. Eider-down, feathers, alpaca, and wool shearling have been used in insulating clothing because of their light weight and high insulating value. Figures 48 and 49 illustrate, respectively, the quilted down and the standard shearling clothing assemblies. The outer coverings should be smooth and snag-resistant. They also must be water-repellent so that rain and snow will not penetrate, but they must not be waterproof, as this causes the moisture given off by the body to accumulate inside the clothing. It is very important that the outer covering have good windbreak qualities in order to prevent the cold air on the outside from passing to the inside and displacing the warm air immobilized in the clothing and around the body. Very close, tight weaves such as are used in the standard issue of the field jacket provide the best wind resistance.

Summary

The final solution for the protection of flyers against the cold will depend on how far the heating and ventilating engineer is able to progress. Proper heating of the airplane is one solution to the problem. At altitudes of less than 30,000 feet, heating systems in modern fighter airplanes are considered to be reasonably reliable. Extreme cold is always encountered in bomber aircraft with exposed turrets and open waists.

Many factors are essential in the design of cold-weather flying clothing. At best, any garment is a compromise among insulation, bulkiness, maneuverability, and availability of material. For extremely low temperatures, insulating clothing is not adequate, and the present types of electrically heated clothing can maintain a seated individual in comfort at a minimum temperature of $-52°C$ ($-62°F$). For most conditions, this protection is adequate.

The problems in protecting the hands and feet are many and difficult. The maximum, practical, insulating protection achieved for the extremities more or less limits the minimum temperatures which can be endured by the individual, even though his body clothing is adequate for lower temperatures. The use of electrical heat in gloves and shoes has developed to such a point that they are almost as adequate as the rest of the electrically heated clothing. Improvements in the oxygen mask, helmet, and goggle assembly have more or less solved the problem of protection for the face.

The effectiveness of clothing for use at low temperatures depends, in the final analysis, on how intelligently it is used. The most extreme conditions which have to be met on a mission should be estimated, the limits of the available clothing known, the proper selection made, and the proper precautions taken in its use. In this manner, clothing will give its best protection in low temperatures.

CHAPTER VIII

VISION

INTRODUCTION.—Of all man's sensory equipment, his eyes are the most important for flying. In contact flying, as well as in acrobatics, vision is the only sense which gives the pilot reliable data regarding the position of his plane in space. Even in so-called "blind flying" the pilot depends almost entirely on his sense of sight. He needs good depth perception for safe landings and take-offs, good visual acuity for spotting enemy planes and targets, good color vision for identifying signal flares and beacons, and good night vision for survival in night operations. Practical considerations such as these have led to the formulation of strict visual requirements in the selection of applicants for flying training in the AAF. Detailed information on criteria and methods of selection of aircrew personnel may be found in the appropriate AAF publications and in the Flight Surgeon's Handbook.

Selection of flying personnel for the excellence of their visual apparatus does not guarantee the most effective use of this apparatus. A man who knows the rules for "good seeing," even though he may have only average visual capacity, is far better off than the man with superior vision who doesn't know "how to see." Primary emphasis in this chapter is on basic aspects of the psychophysiology of vision as they apply to AAF personnel and materiel. An understanding of the principles discussed here will contribute materially to the efficiency of AAF personnel.

Function and Anatomy of the Eye

From the standpoint of function, the visual apparatus may be considered as two separate components. One part operates most efficiently at ordinary illuminations, such as prevail throughout the day and in normally lighted rooms at night. When the illumination decreases to about the level of full moonlight (0.01 effective foot-candles) the other part of the eye takes over. Correlated with this dual function is an anatomical differentiation of nerve endings. The photosensitive layer of the eye, the retina, contains two principal percipient elements, the cones and the rods. The cones (so-called because of their roughly conical appearance), are found densely packed in the central part of the eye, the fovea centralis. Toward the periphery in all directions from the fovea, the density of the cone population decreases and only scattered cones are found in the extreme periphery. The other percipient element, the rods (so-called because of their tubular shape), are entirely lacking in the fovea. Toward the periphery, in all directions to about 20 degrees from the fovea, the density of the rod population gradually increases. Beyond that region the rod density decreases toward the extreme periphery. Also important in this connection is the fact that each cone appears to be connected to a single neuron proceeding to the optic nerve, while a number of rods are usually found to have a common connection in a single neuron. The significance of this structural distinction will be amplified later.

Evidence from several types of experimental work points to the cones as the structural elements associated with day vision, and the rods with night vision. Individual rods and cones differ in sensitivity so that both types of receptors operate over a wide range of illumination. In general, vision at starlight levels of illumination is mediated almost exclusively by the rods, while vision in daylight is largely a function of the cones. Although many of the principles of day and night vision are identical, certain important differences exist. The ensuing discussion will consider cone vision first.

SKY SEARCH.—It is commonly believed that the eye comprehends everything in its field of view with equal clarity and that the retinal image is very much like the photographic image recorded by the film in a camera. This is not the case. By fixating about 5 degrees to one side of some printed material the reader may verify for himself that he is no longer able to read it. The variation of visual acuity with retinal location is shown in figure 50. From an examination of this figure it is seen that acuity is best at the fovea, where the cones are densest, and that it decreases sharply in all outward directions. An appreciation of this fact is learned early in life. In order to see something clearly, one looks at it directly, that is, rotates his eye so that the image of the object he wishes to see falls on the foveal area.

From the standpoint of the combat pilot this distribution of visual sensitivity is a handicap since it prevents him from seeing the entire visible area of the sky with maximal clarity. For self-preservation it is essen-

Figure 50.—Visual acuity of regions of the retina in daylight.

tial that he be able to detect enemy planes at the earliest possible moment. To do so he must continually scan the sky, by rotating his eyes so that successive areas of the sky are brought to focus on or near the most sensitive part of the retina. It is far more difficult to scan correctly than is commonly supposed. Careful experimental studies have revealed that the eye perceives nothing when it is in motion. All reading, for example, takes place during fixational pauses, when the eye is at rest. The reader may verify for himself that in reading the text of this page his eye makes a series of short jumps or saccadic movements. He does not read when his eye is in motion for, if he did, the print would appear as a blur. The importance of this fact should be made clear to every air crewman. In scanning the sky maximum effectiveness is achieved by a series of short, regularly spaced eye movements. Wide, sweeping eye excursions are almost futile and may result in real hazard since they give the impression that large areas of the sky have been examined. The specific pattern of scanning movements must, of course, conform to the requirements of each air crew position and must take into consideration the movement of the plane. Scanning areas or arcs may be worked out for specific positions in each type of aircraft so as to leave no area of the sky unsearched.

VISIBILITY.—The visibility of an object or the ease with which it can be seen depends on: (1) The size of the object; (2) the length of time it is seen; (3) the illumination on the object; and (4) the contrast between the object and its background. These factors are all positively related to visibility; the visibility of any object increases as the size, illumination, time, or contrast is increased. To some extent, a reduction in one of these factors may be compensated for by an increase in one of the others. Thus, an object which is so small as to be just below threshold visibility may be made visible by increasing the illumination on it, or by increasing the contrast between it and its background, or both. Similarly, when the object cannot be seen because of poor contrast, an increase in the size of the object or in the length of time it is viewed may make it visible.

From the military standpoint the size of the object is kept at a minimum, that is, targets and enemy aircraft must be spotted at the greatest possible distance. For this reason, it is important, insofar as possible, to control the other variables so as to make visible the smallest possible target. In scanning and spotting it is usually possible to look at an object for at least one second. Since experimental work has shown that there is little gain in visibility when the duration of viewing is longer than one second, this factor will be discounted in the following discussion.

Visibility and Illumination. — Visibility, or visual acuity, is related to the brightness against which a target is spotted (figure 51). At average brightness levels, acuity increases markedly as the amount of light is increased. At illuminations greater than 1,000 footcandles (as in a heavily overcast day) there appears to be no gain in visual acuity, and there is some evidence

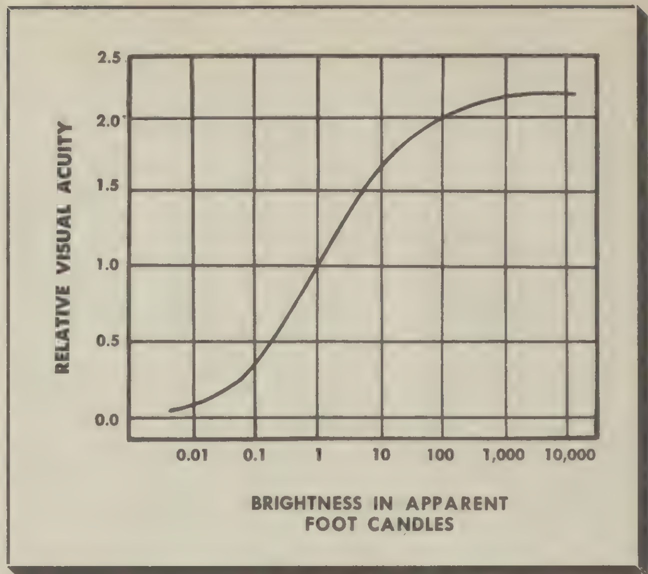


Figure 51.—Relation of visual acuity to brightness of light. (Modified from Shlaer.)

that it may actually decrease at very high brightnesses. Although visual acuity does not suffer under intensities of 10,000 footcandles, most people find the sensation of glare and reflex squinting very uncomfortable. Prolonged exposure to such brilliant light may cause watering of the eyes, photophobia, or even a temporary blindness.

AAF personnel are exposed to extreme and varying brightness conditions which necessitate the use of filters or sun shades. Sunlight reflecting from water, snow, or clouds, or even direct sunlight in the clear air at high altitudes, are sources of glare which may be extremely irritating. Several types of sun glasses and goggles are available to AAF personnel and are listed in the Personal Equipment Officer's Manual and in the AAF stock catalogs. They include the standard flying sun glass with either the light green (50 percent transmission) or rose smoke (15 percent transmission) lens, the type F-1 sun glass for ground personnel in arctic and desert regions, and the B-8 flying goggle (figure 25a) with green (30 percent transmission) lens.

For maximum effectiveness, a sun glass should fulfill certain requirements:

(1) It should absorb enough visible light to eliminate glare without decreasing visual acuity. The most effective compromise seems to be a filter with an over-all visible transmission of about 15 percent. It should be clear, however, that the wearing of sun glasses when the over-all illumination is low, (1,000 footcandles or less) results in a definite loss of visibility (figure 51). Sun glasses are frequently worn indoors and on cloudy days for the purely cosmetic effect. For aircrews who operate only in daylight, this practice is valueless and should be discouraged. Sun glasses should not be worn except on flights when actual glare is present.

(2) The sun glass should be essentially neutral in absorption, or non color-distorting, so that recognition by color will not be impaired.

(3) It should absorb harmful ultraviolet and infrared radiation. This requirement is easily achieved in glass lenses but is much more difficult to obtain in plastics. Recent research has culminated in the discovery of several methods of rendering plastics ultraviolet opaque. Although the reduction of infrared transmission through plastics is a more difficult problem, several possible solutions are being investigated. In general, plastic lenses are very transparent to infrared radiation, and neither the color of the lens nor its absorption in the visible range of the spectrum gives a clue to its infrared absorption characteristics. Because of the danger of retinal lesions from infrared radiation, care should be taken not to view the sun directly through a plastic lens, irrespective of the apparent density of the plastic. Plastic lenses are satisfactory as ordinary sun shades, but should not be used as sun scanning goggles.

Visibility and Contrast. — Contrast may be considered under two headings: brightness contrast and color contrast. The whole art of camouflage depends on methods whereby low color and brightness contrasts are used to conceal objects by decreasing their visibility. Standard camouflage practice for naval aircraft consists in painting the underside a light color (so as to present low contrast against the sky when seen from below) and the topside blue (to match the sea when seen from above). When aircraft operate in one predominant type of combat environment, as do naval aircraft, satisfactory camouflage may be achieved easily. If, on the other hand, the aircraft must operate under a wide variety of environmental conditions, a camouflage for all of these conditions is difficult, if not impossible, to achieve.

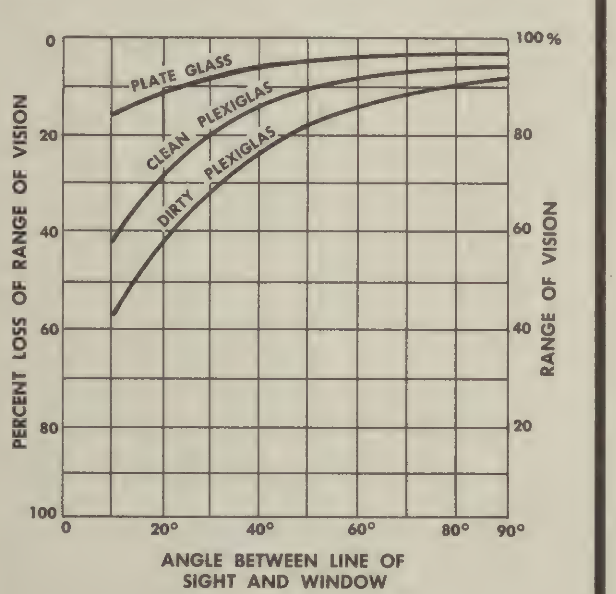


Figure 52.—Range of vision through glass, and clean and dirty Plexiglas at various angles of incidence. (Olenski and Goodden.)

Visibility may be effectively improved by increasing contrast. Perhaps the most important recommendation concerns the necessity for keeping windshields and glasses scrupulously clean. Figure 52 scarcely needs any interpretation. Dust and grease on windshields act as an effective screen between the pilot and the outside world. Particles of dirt and grease scatter light haphazardly into the bundle of light rays which form an image of the object on the retina. This decreases the contrast and destroys the sharpness of the image. Diminished contrast also results from scratching or fogging of the transparent materials because each scratch or water droplet is a source of scattered light. Being softer than glass, Plexiglas is much more easily scratched.

Reflection at all air-glass surfaces results in a loss of transmitted light. When only two surfaces are involved, as with windshields or sun glasses, this loss is too small to be an important factor. However, it becomes an extremely important consideration in optical trains involving many air-glass surfaces. Microscopically thin, low reflectance coatings, usually evaporated onto the glass in a vacuum chamber, have proved successful in decreasing these losses by as much as 90 percent. The optical elements of many instruments, such as range finders, bombsights, and binoculars, are treated in this manner to increase their efficiency. Recently, experiments have been conducted in coating instrument dial cover glasses to reduce annoying reflections from cockpit interiors.

Although the loss of light through windshields and canopies due to surface reflection is a negligible factor, the reflection itself may be a source of trouble. The glint of a canopy in sunlight may reveal the position of a plane long before the plane itself can be seen. In addition, the reflections in the canopy surface of objects in the cockpit may be extremely annoying to the pilot. For these reasons, the possibility of applying low reflectance coatings to windshields has been investigated. Present technics are not adequate for coating large surfaces nor are the coatings durable enough to withstand normal operational abuse.

Color contrast may be used effectively to increase visibility. Of the spectral components of white light the short wave lengths (blue) are most easily refracted and scattered by the atmosphere and suspended dust. This scattering sometimes produces a troublesome diffuseness of retinal images and reduced visual acuity, particularly when dust concentrations are high or when haze and fog are dense. Red, orange, and yellow light are much less easily dispersed by these atmospheric factors. By using a yellow lens to eliminate dispersed blue light it is possible to increase contrast and visibility. This principle is employed in a special amber sun glass (type G-1) issued only to control tower operators, and in the interchangeable amber lenses which are a part of the standard B-8 flying goggle kit.

Standards for Goggle and Sun Glass Lenses

If the glass or transparent plastic through which the pilot looks distorts the pattern of light rays which forms

the retinal image, visibility is impaired. There are two principal sources of distortion which must be considered in this connection; (1) distortion in the lenses of sun glasses and goggles, and (2) distortion in the transparent panels of aircraft. Of the two, only the former has been studied carefully enough so that precise standards and specifications are available.

A good sun glass lens should have lens and prism errors too small to affect the eyes of the wearer. The computation of lens errors depends on the principle of diffraction. A point of light passing through the optical system of a normal eye produces a diffraction pattern, also referred to as a confusion disc, on the retina. Any lens effect which produces a confusion disc on the retina smaller than the diffraction image produced by the eye itself is of no importance to vision. Computations show that an error of 0.06 diopter will produce a vanishing effect on the eye for the normal pupil of 2 to 4 mm. On the basis of practical clinical experience, ophthalmologists have determined the amount of prism which is barely imperceptible to the eye.

Considerations such as these have led to the formulation of precise standards for ophthalmic glass. These criteria appear in section 16 of the National Bureau of Standards Handbook H24. AAF specifications for sun glass lenses conform closely to the recommendations made by the National Bureau of Standards and cover the following points:

(1) The refractive power of the lens measured at the optical center and in the direction of the optical axis shall not exceed plus or minus 0.08 diopter in any meridian.

(2) The difference between the refractive powers in any two meridians, the astigmatism, shall not exceed 0.08 diopter.

(3) Vertical and horizontal prismatic deviation shall not exceed 0.125 diopter.

(4) The right and left lenses of each pair of glasses are matched in sign and power to 0.125 diopter in vertical prism.

(5) The two lenses mounted in any pair of tinted glasses are matched in total visible transmission to within 3 percent.

(6) Glass used for the lenses shall be of high quality ophthalmic crown glass, free from visible or effective striae, bubbles, or flaws which would impair the optical or visual qualities of the lenses.

Plastic lenses used for goggles are usually very much thinner than glass lenses and, therefore, more free from

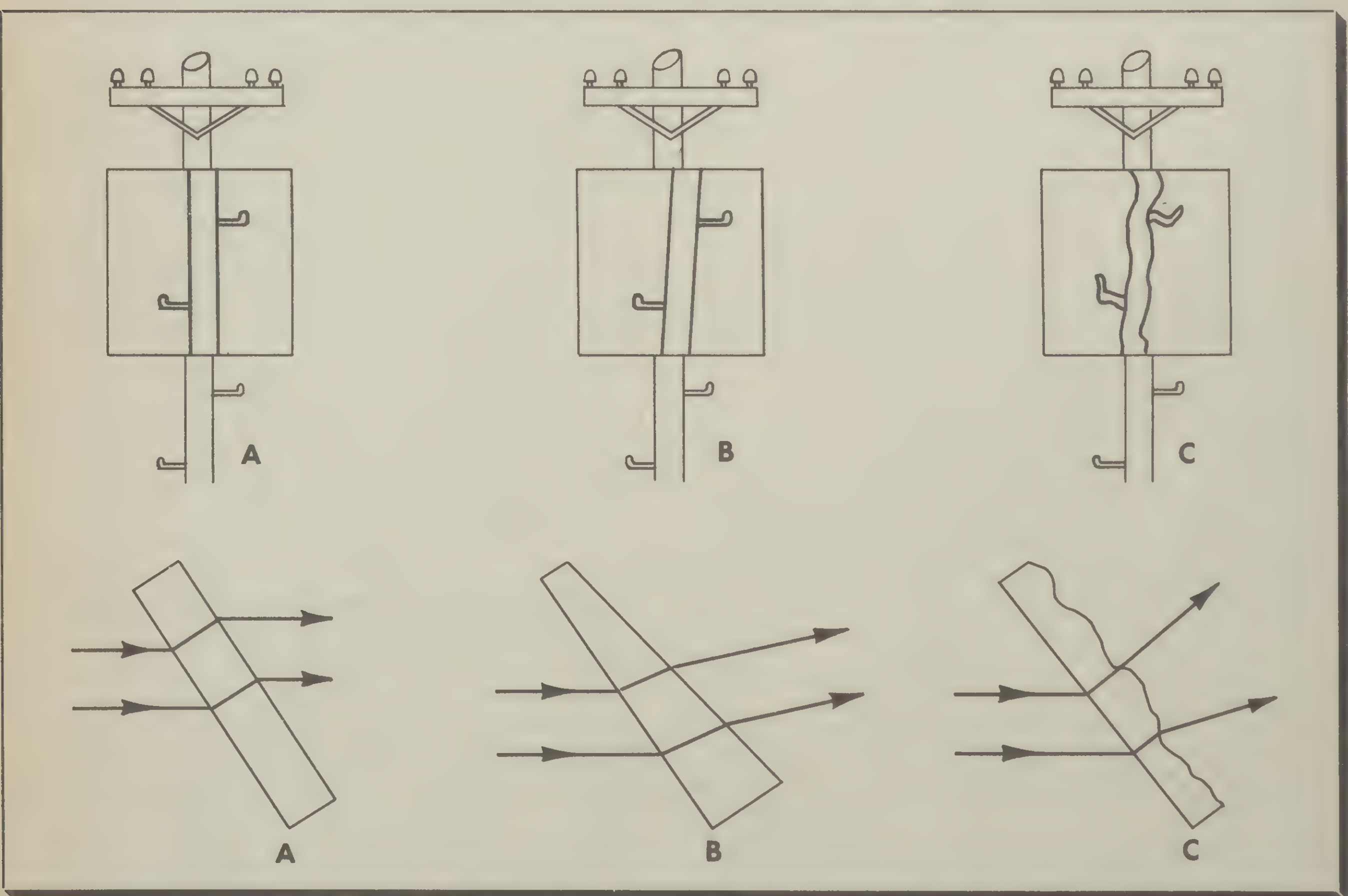


Figure 53.—Panels of glass causing displacement (a), deviation (b), and distortion (c) of light rays. Images of a telegraph pole as seen through the panels are shown.

ERRATA

PHYSIOLOGY OF FLIGHT, AAF Manual 25-2

The following corrections should be made in the text. Offices receiving bulk shipments for further distribution should staple this sheet to inside of the front cover on all copies.

Page 8 - figure 6; write in altitudes on the graph as follows: first vertical line to right of "ground level", 10,000. Continuing to right, label vertical lines 20,000, 30,000, and 40,000.

Page 19 - right column, line 7 - change 12.6 to 11.8

Page 19 - right column, paragraph on "Respiratory resistance" - delete reference to figure 14. This figure applies to the preceding paragraph.

Page 27 - figure 27 - The insert of regulator dial applies only to experimental A-14's. The standard A-14 is not so constructed.

Page 27 - figure 25C - This modification has been replaced in production by the type proposed by the 8th Air Force.

Page 30 - left column - Correct the equation to read as follows:

$$\text{Duration in hours} = \frac{\frac{P}{14.7} \times Vc \times Nc}{14.2 \times \frac{B_A - 47}{B} \times \frac{T}{T_B} \times F_{O_2} \times 60 \times N_M}$$

Page 42 - right column, line 20 - The statement in parenthesis "corresponding to an altitude of 300 ft. per min." is approximately correct for altitudes near sea level. The rate of descent in feet per minute equivalent to a given rate of pressure increase is a function of altitude.

Page 65 - figure 56 - In the graph the curve to the left should be labeled "rod vision" and the one to the right "cone vision"

Page 67 - Chapter IX, left column, line 11 and 12 - delete "and velocity in curved flight"

Page 74 - left column, line 13 - Change 2.0 to 2.5

Page 74 - right column, line 10 - Change G-2 to M-2

Page 76 - right column, lines 6, 7, and 9 - Gas volumes 10.47, 7.67, 1.96, and 2.07 were corrected to 25^{O}C. 760 mm Hg.

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distortion. AAF Specifications for plastic lenses in the B-8 flying goggle kit, for example, are more rigid than for glass in the requirements for prism deviation. Plastic lenses used in AAF goggles afford complete protection from flash burns although they will burn if exposed for some time to the intense heat of an open flame.

Distortion in Aircraft Glass

The problem of eliminating distortion in aircraft windshields and canopies is much more complex than that of controlling the quality of lenses in sun glasses and goggles. The shapes and contours created by the aircraft designer for aerodynamic reasons are not always compatible with the requirements of good visibility. Frequently, the shapes and curvatures planned are impossible to manufacture in transparent panels because they cannot be formed in certain types of complex curves. This is especially true of glass. Of those curves which can be fabricated, the more complex usually create excessive visual distortion because of the stretching and flow of the material during the manufacturing process. This necessitates certain compromises in the design of aircraft canopies and windshields. A certain amount of streamlining must be sacrificed in order to produce acceptable windshields. Until recently, solutions have been reached largely on a trial and error basis. Work is now being done to provide systematic methods for dealing with this problem.

Distortion must be differentiated from simple displacement and deviation. Whenever light rays pass through a piece of flat glass, as in figure 53, they are displaced by refraction. The amount of displacement depends on the thickness of the glass. When the glass surfaces are plane parallel the displacement is always a parallel one, that is, the emergent rays are parallel to the incident rays. Even in thick bulletproof glass the displacement amounts to less than one inch. Since a plane 600 or 6,000 yards away seen through such glass would appear less than 1 inch from its true position, displacement is an unimportant factor.

Aircraft glass is seldom perfectly plane parallel. When the glass surfaces are plane but not parallel light passing through them is deviated as by a prism or wedge. Thus, the path of emergent light rays is not parallel to that of the incident rays (figure 53). The degree of this prism effect varies with the amount of wedginess in the glass. Large amounts of deviation cannot, like displacement, be ignored. With a deviation of only five minutes of arc (1/12 degree) an object at a distance of 1,000 feet will appear to be 1.4 feet from its true position and at 1 mile will appear to be 7.7 feet from its true position. Obviously, bombsights, sextants, and gun sights which are aimed through glass having such inherent deviations will not sight accurately on their targets. The amount by which light rays are deviated in passing through a piece of glass depends not only on the wedge of the glass, but also on the angle at which the glass is placed to the line of sight. Table 8 shows that as the angle between the glass and the line of sight is decreased, the deviation angle increases. For example, a target seen at a distance of 1,000 feet through a panel having a deviation of five minutes of arc placed at an angle of 20 degrees to the line of sight will appear to be 6.9 feet from its true position. In recent aircraft designs windows have been placed at as small angles as 22 and 26 degrees. Considering the degree of deviation involved, such designs become a matter of concern.

TABLE 8

EFFECT OF ANGLE OF INCIDENCE ON INCREASING DEVIATION OF LIGHT DUE TO WEDGINESS OF PLANE GLASS

Angle of Incidence Degrees	*Factor Showing Increase in Deviation*
0	1.00
10	1.03
20	1.11
30	1.26
40	1.53
50	2.02
60	2.88
70	4.79
80	10.9
89	123.7

True distortion is produced when a surface of a sheet of glass is irregular, as shown in figure 53. Light rays passing through any section of such a piece of glass are deviated in an irregular manner. This is the type of error which makes a straight line, such as the edge of a runway, appear wavy or bent when viewed through certain transparent enclosures, as the nose of B-17G. No very satisfactory method has yet been devised for measuring distortion. Three generalizations may be made. Distortion is increased by: (1) Decreasing the angle between the glass and the line of sight; (2) bending the glass into complex curves or into curves of small radius; and (3) increasing the distance between the glass and the observer's eyes.

Night Vision

INTRODUCTION.—In an earlier section of this chapter mention was made of important differences between day and night vision. One of these differences involves color vision. True perception of color is not possible with the rods, as may be clearly demonstrated by trying to determine the color of objects at night. It is possible to distinguish between the light and dark colors at night only in terms of the intensity of reflected light. If, however, the brightness or intensity of a color is above the threshold for cone vision it can be perceived as a true color. For this reason bright signal flares and runway markers can be properly identified at night.

Perception of fine detail, likewise, is impossible at night. Figure 51 shows that when the illumination is very low, visual acuity is greatly impaired. At 0.1 foot-candles, acuity is only one-seventh as good as it is in average daylight. From this it follows that objects must

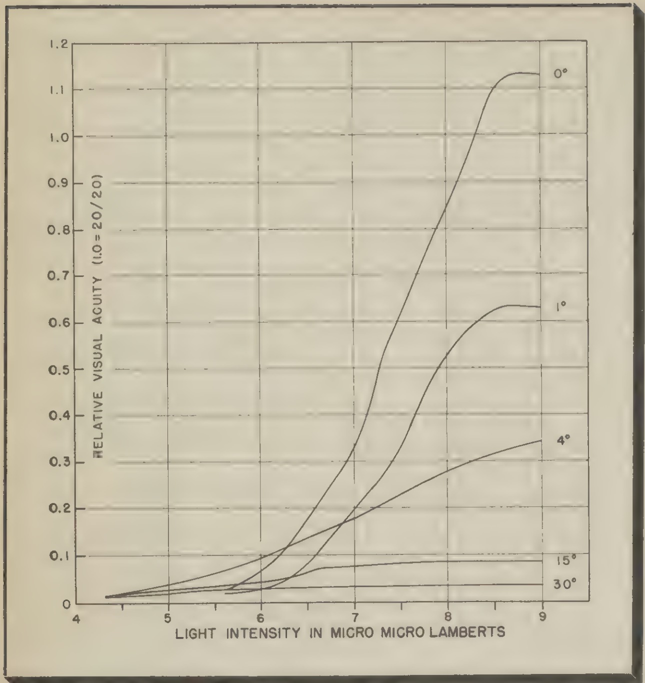


Figure 54.—Visual acuity of regions of the retina. The curves represent varying degrees of eccentricity from fovea. Light intensity below 6 log units represents night vision; above 6 log units, day vision. (Modified from School of Aviation Medicine.)

be rather large or nearby to be seen at night. Aircraft identification at night must depend on the perception of generalized contours and outlines and not of small distinguishing features. The explanation for this loss of acuity is found in the different number of neural connections supplied to the rods and cones respectively, as has been previously noted.

Another important distinction between day and night vision is the differential sensitivity of various parts of the retina under these two conditions. Figure 54 shows the visual acuity of specific sections of the retina at night and may be compared with figure 50 which applies to day vision only. The curves in figure 54 chart a function which results from the distribution of rods in the retina as described in the previous section on the anatomy of the eye. The significance of these data is that the central part of the eye is not the most sensitive at starlight illumination levels. To see things most clearly at night one must not look directly at them. Because of long years of conditioning in looking directly at objects to see them, the average city dweller finds off-center vision unnatural. On the other hand, woodsmen or farmers who spend more time in near or complete darkness know this technic from practical experience. Off-center vision is a practice which can be learned easily. Ideally this should be done by living in the dark for a week or more. Considerable skill may be acquired, however, without resorting to such drastic methods.

DARK ADAPTATION.—Going suddenly from bright light into darkness is a common and frequent experience in modern civilization. This occurs on entering

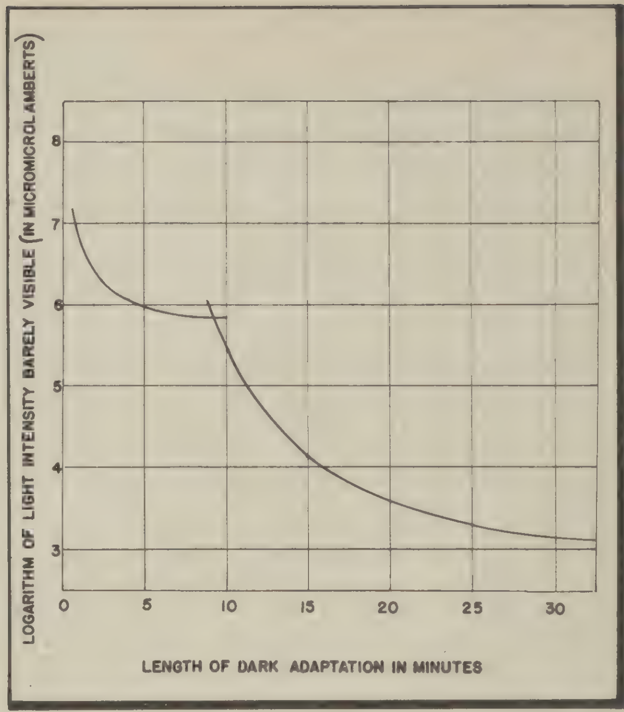


Figure 55.—Normal curve of dark adaptation measured with a 3-degree test light, 7 degrees temporally in the visual field. The absolute cone threshold occurs where the curve levels off between 5 and 10 minutes. The additional increase in sensitivity of the eye is due to function of the rods.

a movie theater during the day or on leaving a brightly lighted room at night. In every case the sensations are the same. At first almost nothing can be seen. After several minutes, dim forms and large outlines become visible, and, as time goes by, more details of the environment become perceptible. This increase in sensitivity at low levels of illumination is called dark adaptation.

Dark adaptation follows a definite pattern which can be charted by determining the minimal amount of light visible at various intervals after entry into the dark. The typical course of dark adaptation plotted against time is illustrated in figure 55. During the first 30 minutes the sensitivity of the eye increases roughly 10,000 fold with little further increase after that time. Under ideal atmospheric conditions, the completely dark-adapted eye can detect the flare of a match 25 miles away.

Dark adaptation may be accomplished in varying degrees and at different rates. In a theater the eye adapts fairly quickly to the prevailing level of illumination which, compared to that characteristic of a moonless, starlit night, is rather high. Less time is required to adapt from the theater illumination level to complete darkness than from the high brightness level characteristic of a hangar interior, for example. Thus, the lower the starting level of illumination, the more rapidly is complete dark adaptation achieved. If the dark-adapted eye is carelessly or inadvertently exposed to a bright light, such as a flaring match at close range, or a

searchlight beam while in flight, the sensitivity of that eye is temporarily impaired. The amount of the impairment depends on the intensity and duration of the exposure and as much as 30 minutes may be required to regain the previous level of dark adaptation.

Effect of Exposure to Sunlight on Subsequent Dark Adaptation.—Recent experimental work has shown that exposure to bright sunlight has a cumulative and adverse effect on dark adaptation. Individuals exposed to intense sunlight for only two to five hours show a definite decrease in their sensitivity at low brightness levels which persists for as long as five hours after exposure. Individuals who normally work in bright sunlight show a considerably retarded rate of dark adaptation and a loss of night visual acuity and range. These effects are cumulative and persist for several days. For this reason, individuals who work in bright sunlight and who are on call for night duties must be provided with suitably dense filters or sun glasses, if their vision at night is to be maintained. Appropriate filters are the AAF standard F-1 sun glass and standard flying sun glass equipped with rose smoke lenses of approximately 15 percent over-all transmission.

Artificial Aids for Dark Adaptation.—The retinal rod cells are much more sensitive to blue light than to red. This is illustrated by the relative visibility curves shown in figure 56. The rods are so little stimulated by red light that by wearing red-lens goggles in ordinary artificial illumination it is possible to achieve complete dark adaptation and still see well enough with the cones to read or write. Wearing such goggles eliminates the need for spending the 30 minute period in a dark room and decreases the possibility of harmful effects from accidental exposure to bright light, especially when going from ready rooms to waiting planes. When the goggle is well designed it can be put on and removed quickly, thus affording the air crewman some protection from the effects of searchlight beams at night. A corollary to the use of red-lens goggles is the use of red light for instrument panels and all interior aircraft lighting to provide good illumination without impairing dark adaptation. The AAF standard dark-adaptation goggle, type E-1, is light, compact, and can be easily folded and slipped into a pocket.

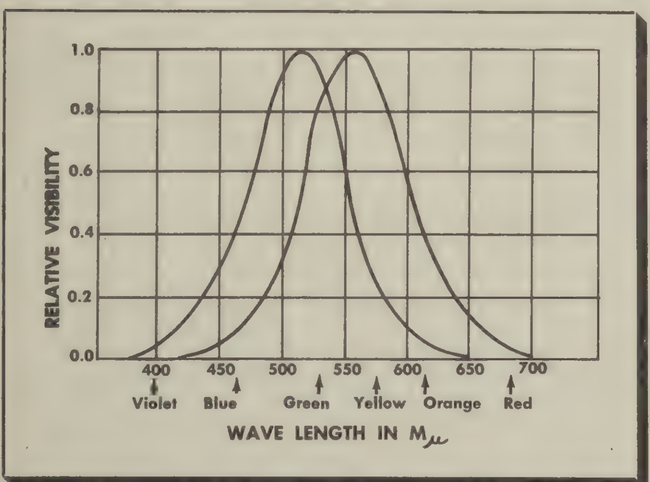


Figure 56.—Relative visibility of various colors of light. (Troland.)

Individual Variation.—There is considerable variation among individuals with respect to their ability to see in dim light. In fact, those with the best night vision can see with only one-tenth the illumination required for similar visual acuity by those with the poorest night vision. A man with good day vision does not necessarily have good night vision. It has been found, however, that the ability to see at night may be increased in most individuals by practicing off-center vision in dim light. The effect of practice is great enough, in most people, to double the efficiency of their night vision.

EFFECT OF ALTITUDE ON NIGHT VISION.—Exposure to reduced oxygen tensions at altitude causes an increase in the time required for dark adaptation and a decrease in ability to see at night. At 12,000 feet, when a flyer is breathing atmospheric air without supplemental oxygen, night vision is only about one-half as good as at sea level. For this reason, the use of supplemental oxygen from the ground up is required on all tactical and combat night flights (AAF Regulation No. 60-7, 2 February 1942). One hundred percent oxygen is not required, since the object of its use is to maintain the blood oxygen content at approximately sea level concentrations. Therefore, the automix of the demand oxygen regulator should be set in the "ON" or "NORMAL OXYGEN" position.

CARBON MONOXIDE AND NIGHT VISION.—Anoxia due to carbon monoxide poisoning affects visual acuity, brightness discrimination, and dark adaptation in the identical way and extent as do like degrees of anoxia resulting from high altitudes. As an example, it has been shown that 5 percent saturation with carbon monoxide has an effect on the visual threshold equal to that of an altitude of about 8,000 to 10,000 feet. Smoking three cigarettes may cause a carbon monoxide saturation of 4 percent, with an effect on visual sensitivity equal to that of an altitude of 8,000 feet. These facts stress the importance of minor concentrations of carbon monoxide in the cockpits of planes involved in night flying.

EFFECT OF FOOD ON NIGHT VISION.—Vitamin A is a chemical factor essential to good night vision. This vitamin is normally supplied plentifully in Army rations. Each individual should know and eat the foods which contain vitamin A or carotene. Foods high in vitamin A content are eggs, butter, cheese, liver, apricots, peaches, carrots, squash, spinach, peas, and all types of greens. Cod-liver oil and greens are richest in vitamin A. Although an excess of vitamin A will not improve the night vision of a normal individual who is already getting enough, it will do no harm. When conditions make it impossible to provide foods containing vitamin A in a quantity sufficient to maintain good night vision, supplemental doses of this vitamin should be provided as directed by the flight surgeon. Multivitamin capsules (Medical Department Supply Catalogue, Item No.

1-K61500) contain vitamin A. (See AAF Memorandum No. 25-5, 14 July 1942, for further details.) The importance of vitamin C for night vision has not yet been completely ascertained, but it is possible that a diet deficient in vitamin C may lead to impairment of night vision. Recovery from vitamin deficiencies may be slow, especially when the avitaminoses have developed from prolonged periods of reduced vitamin intake. Complete recovery from chronic avitaminosis may require several weeks, though it has recently been claimed that large doses (10,000 units three times a day) of vitamin A shorten the recovery period appreciably.

VISIBILITY AT NIGHT.—The factors which affect visibility at night are essentially the same as those previously considered in the section on visibility in daylight. Since far less light is available at night, the flyer's ability to see through the windscreen of an aircraft is more easily impaired under this condition than in daylight. The light absorbed and reflected by the windscreen is no longer an unimportant factor since it represents a considerable proportion of the light available. The decrease in contrast between an object and its background because of reflections by the interior surface of the windscreen of any light within the airplane is also magnified at night. For these reasons, dirt, grease and scratches on canopies and windscreens are a serious handicap at night. Since the windscreen is indispensable, these factors must be reduced to a minimum. Hence, for night operations, all transparent panels must be kept scrupulously clean and lights within the airplane must be turned out or kept as dim as possible. Since visibility depends so much on contrast, a pilot can make his own ship less visible and enemy aircraft easier to spot if, when flying over dark land and under a light sky, he stays below the enemy, and, when flying over white clouds or snow, above the enemy.

Since visual acuity at night is so poor, (figure 54) the size of objects becomes of extreme importance. An enemy plane can be seen from about 1,000 feet at night, but only if it is viewed from above or below so that its greatest aspect is seen. For this reason, night fighting tactics require that enemy aircraft be followed either from rear-above or rear-below, rather than from straight rear-level. Otherwise, its silhouette is small and may easily be lost to view.

Visibility of Colored Lights and Surfaces at Night.—Red and blue-green lights, or surfaces of equal size and brightness at ordinary levels of illumination do not remain equally bright as the distance from them increases and the rods become increasingly active in seeing them. Blue-green "outlives" other colors in visibility as the distance between the light source and observer increases. This is known as the Purkinje effect and is related to the differential sensitivity of the rods and cones as shown in figure 56. The magnitude of this shift in sensitivity of the eye to light of longer and shorter wave lengths, respectively, is enormous, and may amount to a factor of as much as 1,000. Thus, blue and green lights can be much more easily detected at night by a distant enemy observer whose eyes are dark adapted.

In addition to the fact that reddish light is less visible at a distance, it is also desirable for military night lighting because visual acuity under red light is much better than under blue light of equal brightness. Thus, the use of red light facilitates the reading of maps, charts, and instruments at night without impairing dark adaptation.

Red light is preferable, therefore, for the illumination of objects exposed to enemy observation. In order of decreasing value, dim orange, yellow, or white lights may be used. The use of green and blue lights should be avoided.

Autokinetic Movement

A person who stares at a fixed light in an otherwise dark room will soon experience the illusion that the light has begun to move erratically. This illusion is known as the autokinetic phenomenon. If he stares at the light long enough, he may become almost hypnotized by it, so that it takes up all his attention, and he is almost unconscious of everything except the "moving" light. If a pilot is flying in a tight formation at night and stares fixedly at a tail-light ahead, he may go out of formation and crash trying to follow its apparent movement. Although the exact cause for this illusion is not known, it may be prevented or dispelled by continually shifting fixation from point to point.

Size-Distance Illusion

The size-distance illusion results from staring at a point of light which approaches and recedes from the observer. In the absence of additional distance cues, accurate depth perception is extremely difficult. Instead of seeing the light advancing and receding, the pilot has the illusion that it is expanding and contracting at a fixed distance from him. This illusion may also be dispelled by shifting fixation continually.

It has been recommended that twin tail-lights with a standard separation be adopted for all types of aircraft. This would result in the following:

(1) Autokinesthesis would be greatly relieved or eliminated.

(2) Distance estimation and depth perception would be greatly simplified.

(3) The position of the two horizontally placed lights would provide a basis for judging the attitudes and maneuvers of the leading plane in a formation.

In summary the following suggestions may be given to flyers for improving visual efficiency:

(1) Know how to scan properly and work out an efficient skysearch plan for your particular aircraft and position. Short, regularly spaced eye movements will enable you to see more than wide sweeping movements. This applies as much at night as during the day.

(2) If you are not on call for night duties wear sun glasses only when you need them to eliminate glare.

(3) If you are on call for night duties wear sun glasses during the day.

(4) Keep all windscreens scrupulously clean.

(5) Preceding any night operation, dark adapt by staying in a dark room or by wearing red-lens goggles for 30 minutes.

(6) To preserve dark adaptation do not expose the eyes to any bright light.

(7) Turn out all nonessential lights within the aircraft and keep all essential lights as dim as possible.

(8) Use red light whenever possible at night.

(9) Improve night vision by practicing off-center viewing of objects on dark nights.

(10) Use supplemental oxygen from the ground up on all night flights.

(11) Include foods containing vitamin A in the diet.

(12) Do not stare at isolated points of light at night.

CHAPTER IX

EFFECTS OF ACCELERATION ON AVIATORS

PRINCIPLES OF PHYSICS.—A clear understanding of the effects of acceleration on flying personnel requires a knowledge of the physical forces involved. Acceleration is a generic term for "a change in velocity," either with regard to magnitude or direction, or both. When velocity increases, the change is called "acceleration;" when velocity decreases, the term "deceleration" is used. Three types of acceleration and deceleration are encountered in flying: *linear,* involving change of speed in a straight course; *angular,* a change in rate of rotation; and *centripetal,* a change of direction and velocity in curved flight.

Linear accelerations or decelerations are those in which the magnitude, but not the direction, of the velocity is changed. Examples of their occurrence in aviation are take-offs, landings, catapult take-offs, crash landings, and impacts from parachute openings. In some of these instances the body is subjected to an increase in linear velocity; in others it is subjected to a decrease. Except for the serious results of crash landings, linear accelerations produce no important problems in current aircraft.

Angular accelerations, such as those produced by spins, affect the body chiefly in that they produce dizziness. This problem will not be considered here.

Centripetal Accelerations

Centripetal or radial accelerations, because of their pronounced effects on the human organism, are given chief consideration in this chapter. A body, such as an airplane and its occupant describing a circular path, is subject to centripetal acceleration which sets up a force of inertia called "centrifugal force," acting away from the center of rotation. This type of acceleration is experienced in turns, interruption of dives, loops, or any departure from straight line flight. The amount of centrifugal force produced in these maneuvers is directly proportional to the square of the linear flight velocity of the aircraft and inversely proportional to the radius of its curved path. The shorter the radius of turning at a constant linear velocity, the greater the resultant centrifugal force. The greater the linear velocity, the greater the force. For example, if a given force is being developed at a certain radius of turn and speed, doubling the radius will produce one-half the force. If a given force is being developed at a given speed and radius, doubling the speed will produce a force four times as great. The pilot takes advantage of these facts when he eases up on the stick in a pullout. He is increasing his radius of turn and consequently decreasing the centrifugal force produced.

Figure 57 graphically illustrates the dynamic relationship between radius of aircraft turn and air speed in the production of a given magnitude of centrifugal force. Figure 58 correlates this relationship in the production of varying magnitudes of centrifugal force.

As a convenient measure of centrifugal force, the unit representing acceleration due to gravity, that is, 32 feet per second per second, is represented by the symbol "G." By common usage, accelerations in which the flyer is pushed down in the seat are called *positive accelerations* (+ G). Conversely, in *negative acceleration* (—G) the flyer is lifted out of his seat. A man seated in a chair is pushed down with a force of + 1 G*. If he were

*Hereafter, positive acceleration, or +G, will be referred to as G. Negative acceleration will retain its minus prefix.

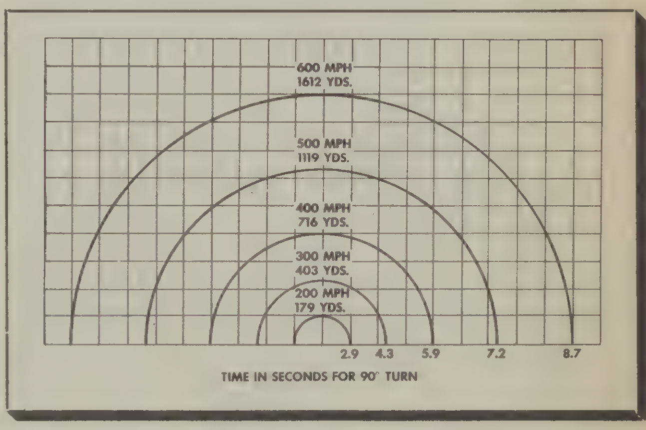


Figure 57.—Radius of aircraft turn required to produce blackout (5 G) in the average pilot at various true air speeds.

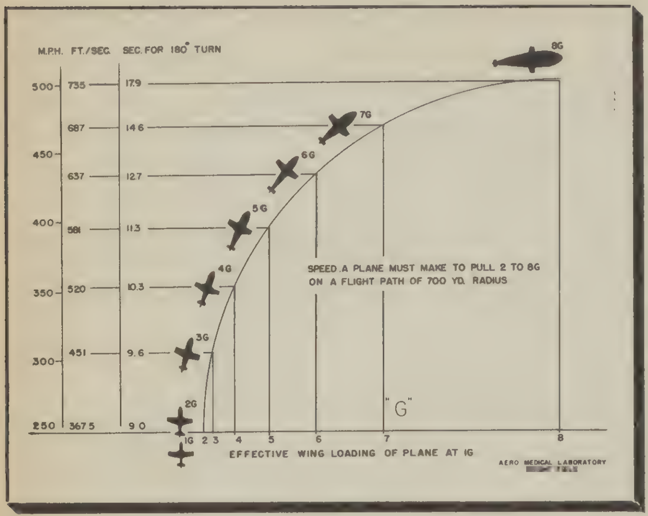


Figure 58.—Relation between radius of aircraft turn and air speed in the production of various magnitudes of G.

pushed down twice as hard, the force would be 2 G. Effectively, then, he weighs twice as much, and the strain on his supportive structures likewise is twice the normal amount. The effects of centrifugal force are determined by (1) its direction with respect to the body, (2) its magnitude, and (3) its duration.

EFFECTS OF POSITIVE ACCELERATIONS.—The subjective effects of positive accelerations can be summarized as follows: At lower centrifugal forces, such as 2 G, the subject is pressed firmly into the cockpit seat; at 3 to 4 G, upward movements of the extremities become difficult or impossible and the soft tissues of the face (figure 59) and the body are drawn downwards; at 3-½ to 5 G, acting over a period of three to five seconds, visual disturbances begin.

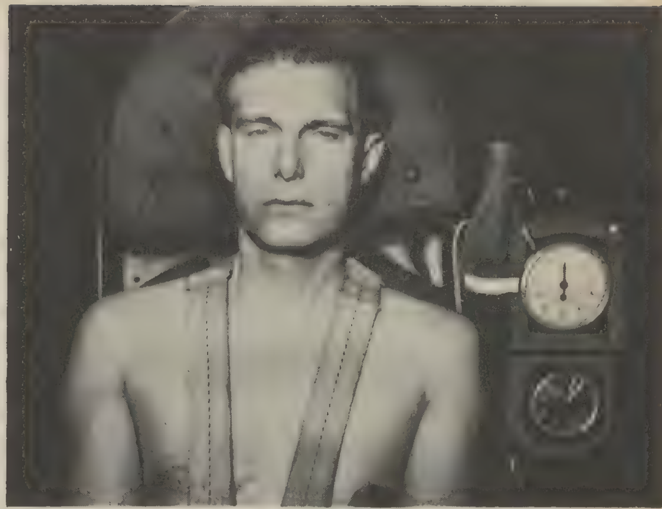
The visual disturbances are blurring or "graying" of vision and narrowing of the visual field, followed by "blacking out," which is loss of vision without loss of consciousness (figure 60). The degree of visual change experienced by any individual is a function of the magnitude and duration of G. When force is low, as at 3 to 5 G, about 5 seconds is required to produce the physiological effect. It is doubtful whether prolonged continuance of a low force can produce a greater physiological effect than the first 10 seconds of the force produces. Actually, the compensatory cardivascular effects at low G values usually produce some clearing of symptoms after the first 10 seconds though the force may continue unabated. As the G force rises above the tolerance of the ordinary man, that is around 7 to 9 G, the time required for blackout to occur decreases considerably, falling to as low as two seconds. That is probably the minimum time for forces which do not stun the man to produce blackout. Other disturbances occurring in association with blackout may be a decreased sharpness of mental perception and judgment. At or above 5 or 6 G, consciousness may be lost within five seconds. Except when consciousness is lost, symptoms disappear almost immediately on cessation of the centrifugal force. When consciousness is lost, 5 to 35 seconds are required for it to return. There will then follow a period of confusion which may last for 20 seconds. Most flyers do not differentiate clearly between blackout and unconsciousness. In true blackout orientation is maintained, hearing is preserved, and vision is absent. Recovery is rapid when force abates. In unconsciousness the flyer often dreams; he is slow to awaken and disoriented when he does so. Spontaneous clonic muscular movements may occur. There follows a variable period during which the previous train of thought and action has to be reconstituted.

Among subjects undergoing positive acceleration, an increase in pulse rate together with a decrease in blood pressure above the heart has been found. *(See figure 61.)* The respiratory rate similarly increases. The visual and mental disturbances resulting from positive acceleration are due to a decreased blood flow through the brain and eyes. There are several theories as to the cause of this impaired circulation.

With the subject in the normal sitting position, G acts in a direction parallel to the main blood vessels of the body. As a result of G force, the blood weighs more than it does normally. The existing head of pressure forcing blood out through the somewhat constricted arteriolar limb fields increases because of this greater weight. As a result the peripheral run-off of blood into capillaries and veins of dependent portions may be increased. Unless peripheral constrictions of arterioles were marked and prompt, the arterial pressure level would fall markedly. The relative increase in the weight of the blood also reduces the effective head of pressure forcing blood to the brain. Under 1 G, the column of blood above the heart is about 25 cm; at 4 G it is equivalent to 100 cm. Thus, very much more of the pressure is wasted simply in supporting the column and less pressure remains to produce circulation through the capillaries. Present evidence indicates that at moderate G's the systolic pressure at heart level remains around 120 mm Hg. At 5 G, in a man of normal height, this would leave no pressure head to force flow in the capillaries of the brain.

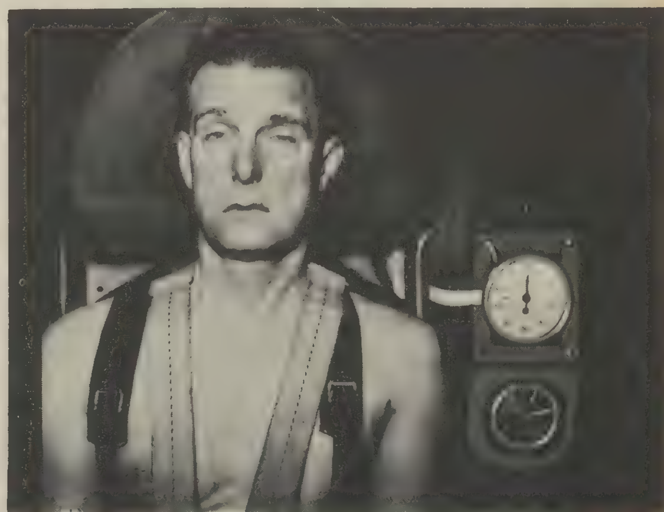
A second possible cause of the cerebral anoxia may be that the increased hydrostatic pressure existing in the arteries and veins under G tends to distend them. The thick-walled muscular arteries resist distention, but the thin-walled veins distend and increase the capacity of the venous system. As a result, blood is pooled in the abdomen and in dependent portions of the body. Venous pressure, which normally aids in filling the heart, may be unable to overcome such a high hydrostatic pressure and consequently return of blood to the heart may be impeded. Since the heart can pump out only that amount of blood which it receives, circulation may be seriously impaired. Thus two factors account for poor blood supply to the head during G: venous pooling, and relative insufficiency of the forward power of the heart. Roentgenographic studies have permitted visualization

1G

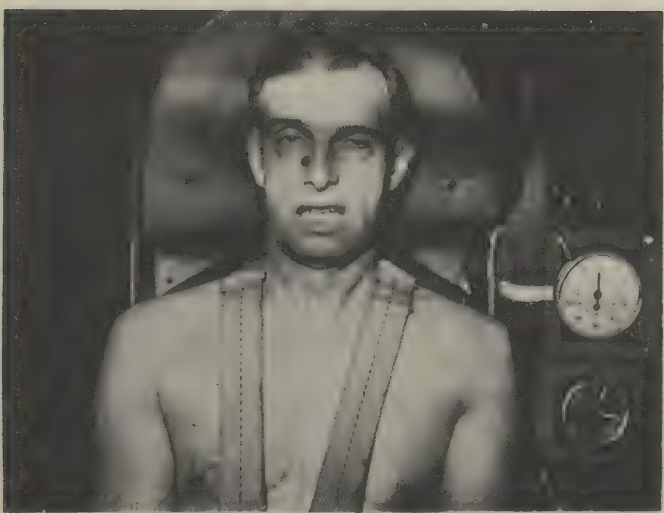


2G

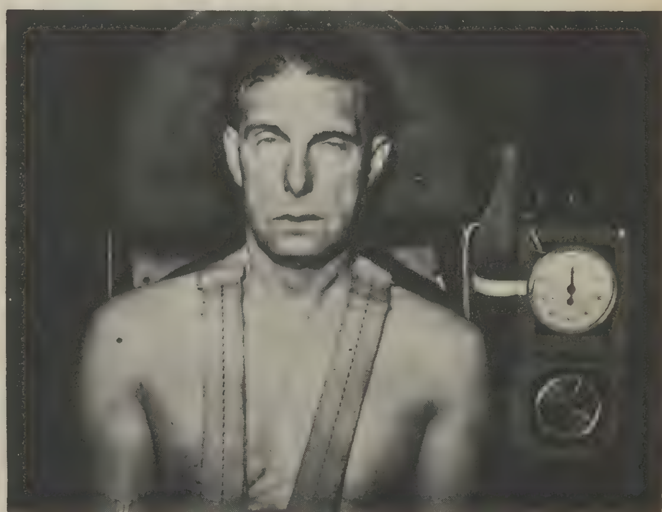
3G



4G



5G



6G

Figure 59. — Subject undergoing positive acceleration. The photographs were taken in separate experiments. The magnitude of G may be read on the dial of the accelerometer at the right.

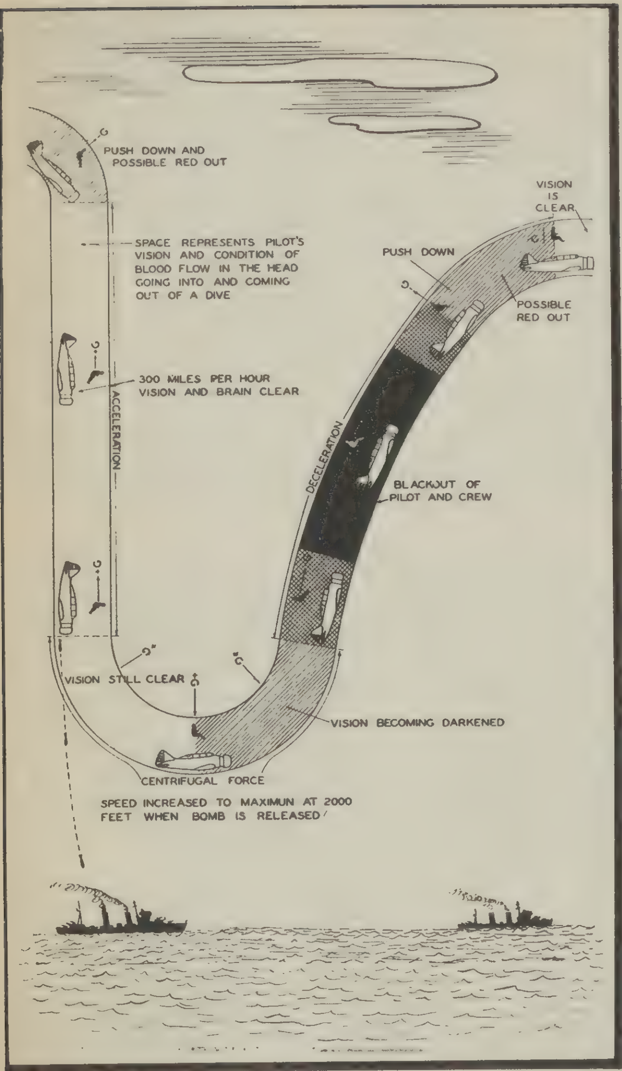


Figure 60.—The effects of acceleration, deceleration, centrifugal force and "push-down."

of the heart during exposure to G (figures 62a and b). Observations through artificial windows in the skulls of animals have made it possible to study the flow of blood in the brain during exposure to G on the centrifuge. These data have as a basis studies carried out on subjects in a centrifuge, which is a laboratory device used to obtain high centrifugal forces. The apparatus usually consists of a horizontally rotating superstructure, at the ends of which cockpits are suspended.

In man the blood supply to the upper part of the body during exposure to G on the centrifuge has also been determined by photoelectric means. The subject sits in the centrifuge cockpit in a typical cockpit seat (figure 63). He wears a plaster of paris helmet from which a photoelectric ear piece is suspended. Behind the ear is a light and in front of it a photocell. The amount of light penetrating the ear and reaching the photocell is recorded on photographic paper by means of an amplifier. Depending on the type of amplifier used, the ear pulse alone can be recorded with large excursion, or the change in total blood content along with the pulse in much smaller excursion, as in figures 64 a and b. When the G force comes on, the ear pulse at once becomes more rapid and much enfeebled. After 4 to 6 seconds the pulse disappears entirely. (See the middle of the record in figure 64 b.) At the same time, the blood is draining from the ear and the blood volume tracing shows a marked fall and plateau until G force is withdrawn.

The correlation between ear pulse or volume changes and the visual symptoms is excellent in most cases. Visual changes are measured on the centrifuge by means of a series of lights turned on by the observer and turned off by the subject. One set of lights is placed peripherally in the subject's visual field and another is placed centrally. A signal system records the responses on the photographic records. The figure at the bottom (below the time markings) shows the responses to the lights, as well as to a buzzer used to record auditory perception. In the record shown (figure 64 b) it will be noted that four seconds after the ear pulse disappears and the ear density reaches a plateau the peripheral lights are left on (continuous black line). Similarly, the central light fails after nine seconds and yet the subject still responds to the buzzer. This is true blackout; the subject is blind but still hears. It is not unconsciousness. It is difficult to understand why, if the ear pulse ceases, the subject remains conscious. At present only a rather unsatisfactory explanation can be offered; that the ear pulse is not the brain pulse. Further study may reveal the answer to this and other interesting questions.

It appears valid to conclude that the decreased blood flow through the head causes oxygen want, a situation to which the brain, especially the visual mechanism, is very sensitive. Vision is affected first,* and finally the entire brain ceases to function and temporary unconsciousness results. Although the evidence is not yet complete as to the relative importance of the venous return, the heart's ability to pump blood, and the height of the arterial pressure when the subject is exposed to G, theories advanced on the basis of these concepts have led to certain practical applications.

Flyers are aware that their G tolerance undergoes some daily variation. As a rule, this does not exceed 1 G and some evidence exists that it is due to the variation in the arterial blood pressure level just before G is applied. Tolerance for G is affected greatly by pre-existing febrile illness, probably because of the resultant low blood pressure. Emotional tenseness, fear, and excitement raise the G tolerance appreciably and, what is more important, alter the pattern of the symptoms. In extreme cases,

*Visual symptoms occur before a disturbance of consciousness because the normal intraocular pressure (18 mm Hg) tends to act as counterpressure against the arterial blood pressure. This intraocular counterpressure must consequently be overcome before blood can enter the retinal vessels. Since no analagous counterpressure has to be overcome by blood entering the vessels of the brain, a given level of blood pressure may be sufficient to keep the brain, but not the retina supplied with blood.

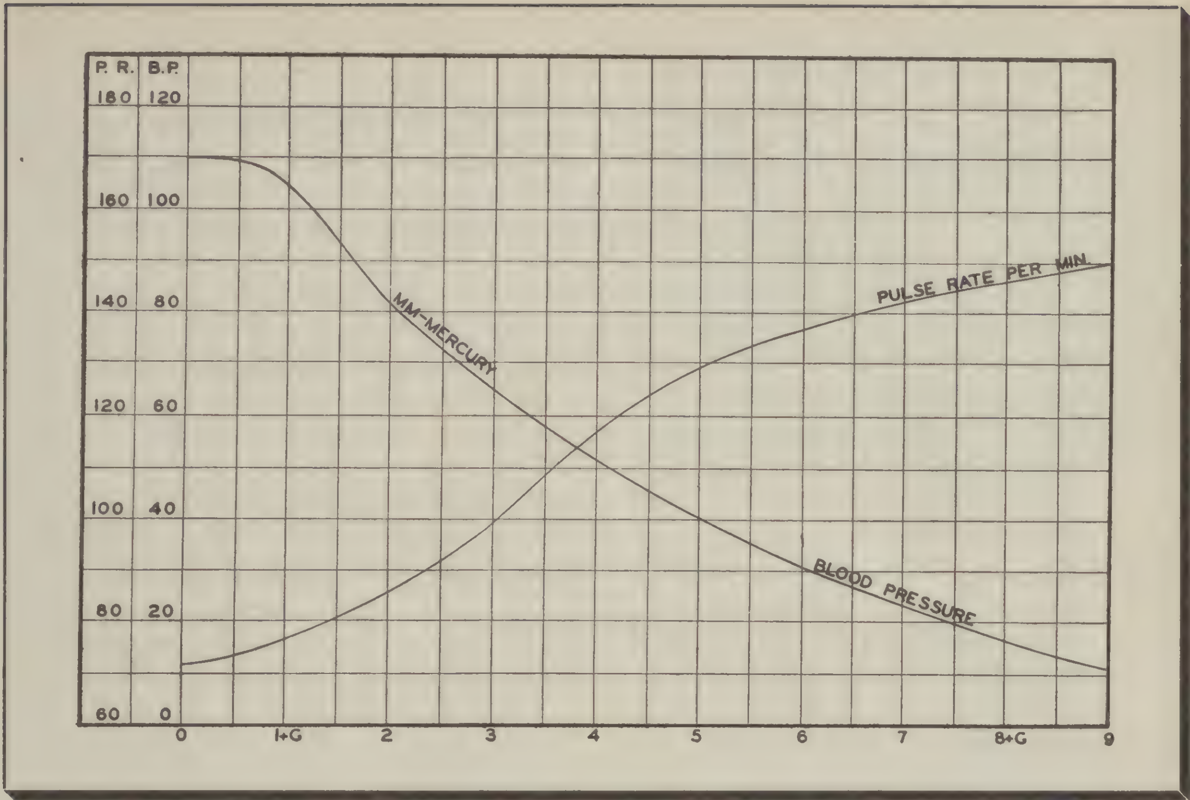


Figure 61.—The effects of positive acceleration upon blood pressure in the head and pulse rate.

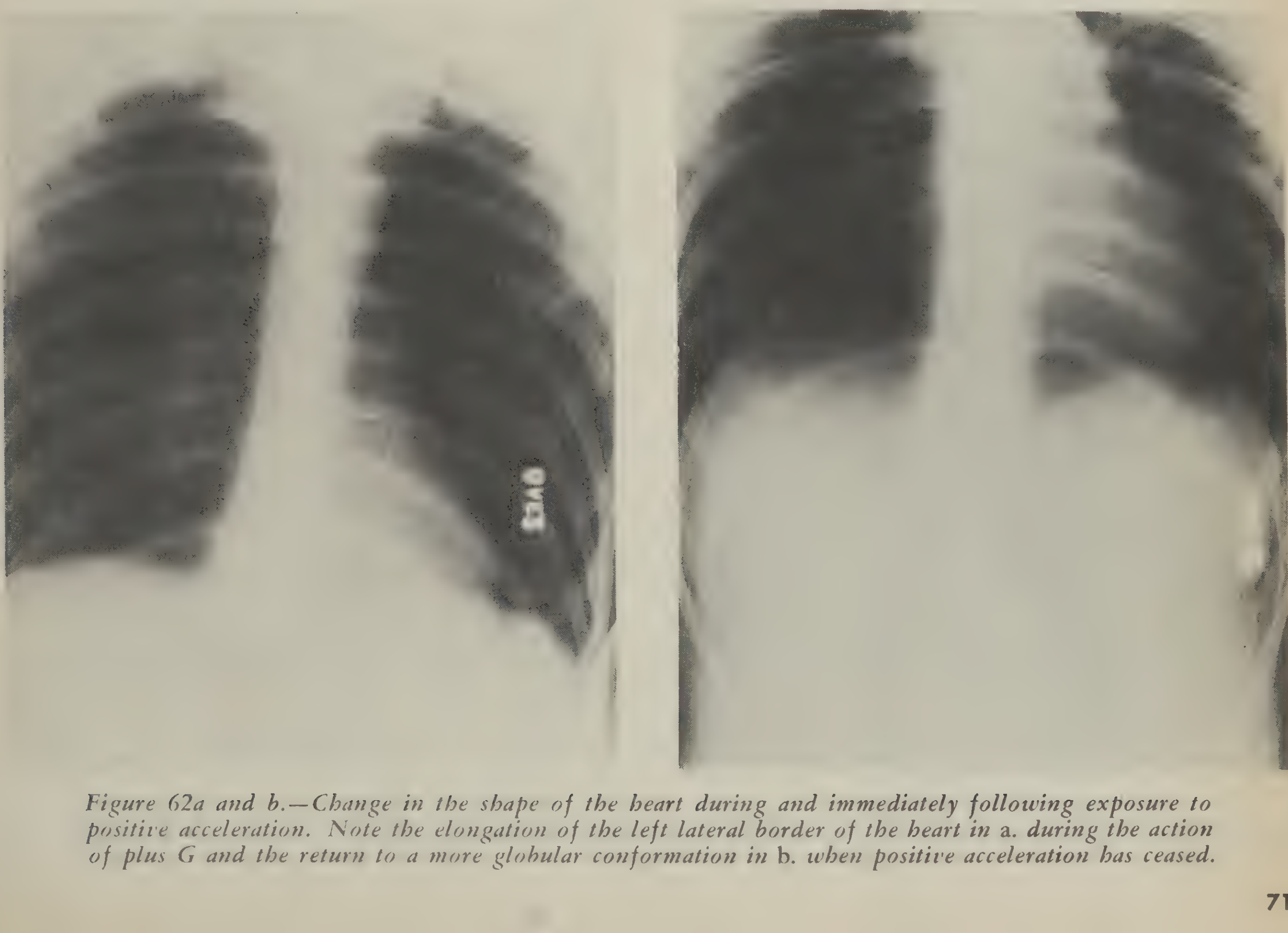


Figure 62a and b.—Change in the shape of the heart during and immediately following exposure to positive acceleration. Note the elongation of the left lateral border of the heart in a. *during the action of plus G and the return to a more globular conformation in* b. *when positive acceleration has ceased.*

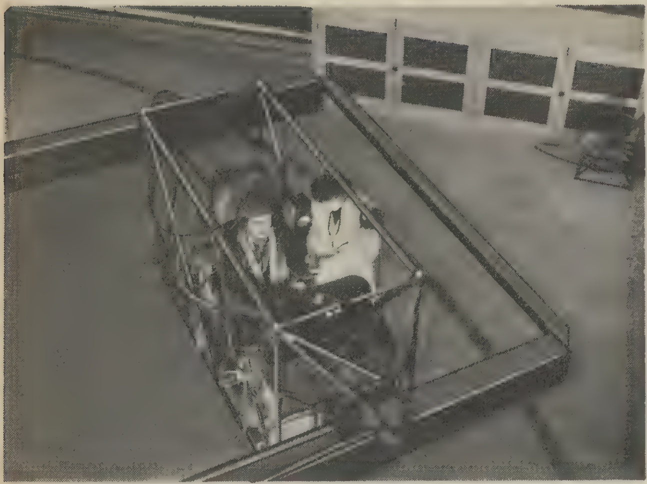


Figure 63.—Cockpit of centrifuge.

clear vision without dimming or blackout may be maintained at all G levels up to a critical value at which unconsciousness supervenes. A relationship between the pressor action of fear and this phenomenon is suspected.

Centrifuge studies confirm aircraft experience in showing that no increased tolerance to positive acceleration is gained with repetition of the exposure to G force over a period of days or weeks. Indeed, with the decrease in nervous tension and fear, as aerobatics become commonplace, the tolerance for G falls.

Experienced pilots have learned to raise their G tolerance by tensing their muscles as they pull back on the stick. Many of them also shout at the same time. These actions are pressor in effect. However, with any action similar to this which falls into the form of a Valsalva maneuver (strong straining against a full chest *with glottis closed*), a relatively low G force will produce unconsciousness. The Valsalva has a marked depressor effect. Thus, shouting is a benefit both directly and in preventing the Valsalva effect.

It should be reiterated that graying or blacking out due to positive acceleration occurs at a lower value of G than does unconsciousness. It is important to remember that in sudden exposure there is no blackout period; if the force is great enough, unconsciousness occurs without warning. In aircraft, this is encountered in snap pull-outs where high forces are applied very suddenly.

EFFECTS OF ACCELERATION ACTING TRANSVERSELY TO THE LONG AXIS OF THE BODY.—The tolerance of human beings to centrifugal forces is greater when they assume the prone position—that is, when the centrifugal force acts at right angles to the long blood vessels of the body. Roengenographic evidence obtained in study of animal subjects in the prone position has demonstrated that no shifting of blood takes place and filling of the heart remains normal at extremely high accelerations. Human subjects have been able to withstand 12 to 14 G acting transversely for 120 to 180 seconds. Interference with respiration is the chief discomfort caused by transversely acting centrifugal forces if the body is properly supported. In present aircraft, transverse forces are encountered only in accelerated take-offs and in arrested landings.

EFFECTS OF NEGATIVE ACCELERATIONS.—In this type of acceleration, the limit of man's tolerance is reached at the comparatively low values of —2 to —3 G. An aviator exposed to such a force suffers from ocular and cerebral congestion. There is a "gritty" sensation in the delicate membranes which line the inside of the eyelids and in front of the eyeballs. The eyeballs feel as if they would pop from their sockets, and there is a throbbing pain in the head. At —3 G a sensation of seeing red or "red-out" has been described. Headache may persist for several minutes to several hours after exposure to negative acceleration. Serious complications, such as retinal and cerebral hemorrhages, can be anticipated if values exceeding —3 G are encountered. Objective signs are a decrease in pulse rate and no particular change in the blood pressure. The physiological basis for the symptoms is a shifting of the blood toward the head, since the centrifugal force is acting in that direction. The cranial cavity is rigid and does not permit much pooling of this blood; hence, there is early congestion, and finally cerebral hemorrhage may ensue. During flight, —G is encountered in outside loops and push downs. Because of the unpleasant character of the symptoms, flyers tend to avoid —G.

The Tactical Answer

Solutions to the fighter pilots' problem of G are varied:

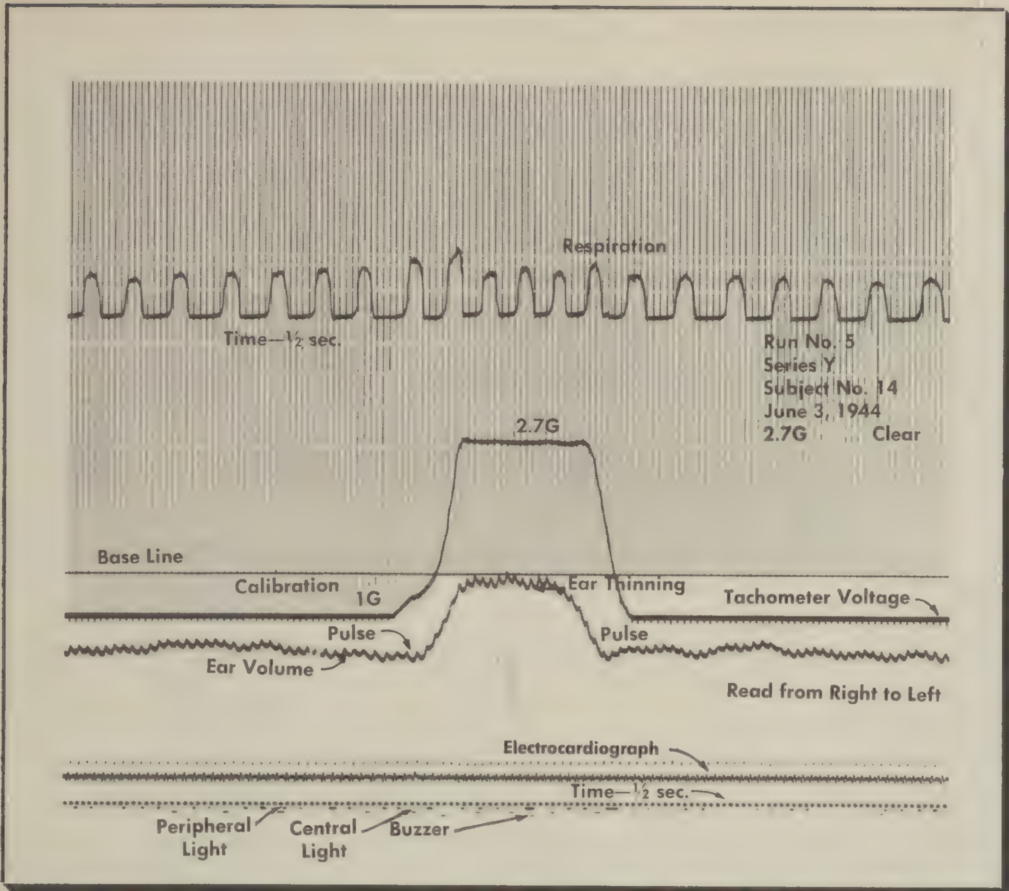
1. Using tactics which evoke little G.

2. Building cockpits which by postural placement reduce the effect of G on the flyer.

3. Having the flyer protect himself by crouching, straining, and yelling.

4. Providing the flyer with a protective device. The use of G-reducing tactics makes it difficult for a fighter plane to engage in combat effectively. Building cockpits in such a way as to reduce the effect of G has been done by the Germans, but it is of limited effectiveness. Furthermore, it is poorly adapted to our deep cockpits and high gun sights. It reached its acme in the now obsolete German prone position fighter. Crouching, straining, and yelling are disadvantageous in that they are fatiguing, they interfere with firing because the crouched pilot cannot line up the gun sight with his target, and they hamper self-defense, for the crouched pilot cannot scan the skies behind him. The principal disadvantage in the use of a protective device is that it adds one more item to the equipment of the pilot. It has, however, none of the disadvantages outlined and has proved popular with pilots wherever tactical advantage could be gained by acrobatic flying.

Anti-G Devices.—Since the immediate cause of blackout is pooling of blood in veins or excessive run-off of blood from arterioles, it was predicted that external pressure on dependent parts of the body would lessen



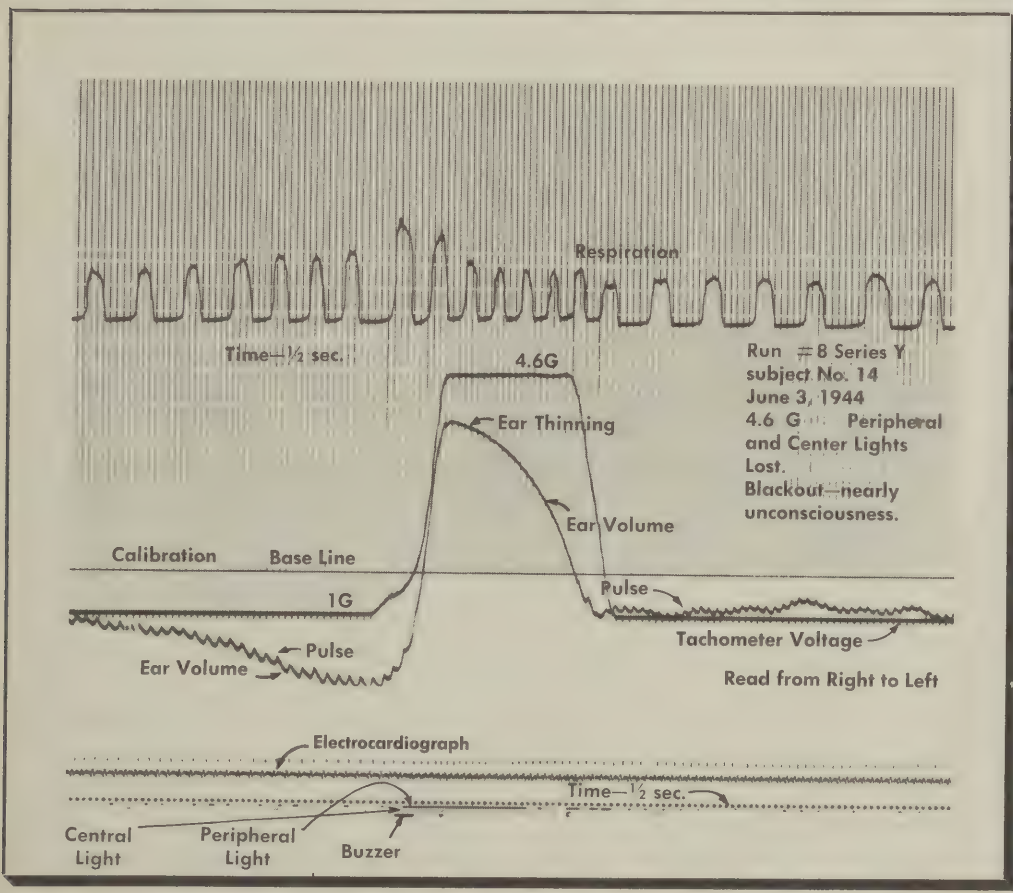


Figure 64a and b.—Typical records of subject's reactions during exposure to plus G in human centrifuge. Reading from bottom up, the three lowest lines record the response to the buzzer, central light, and peripheral lights.

the effects of G forces. The first application of pressure for this purpose in America was a belt produced for test pilots, a device with a bulb like that on a sphygmomanometer. When the pilot was to pull G, he would pump the belt up by hand preparatory to his pullout. Although the pressure was not controlled and the protection poor, the pilots found it beneficial.

At present, several types of devices, descendants of that primitive belt, are in operational use. The most recent device places pressure upon the calves, the thighs, and the abdomen. Pressure is mechanically produced and automatically administered whenever the G force on the plane exceeds 2. The pilot needs only to plug his suit in when he climbs into the aircraft.

The suit itself, after various modifications, has been simplified to the minimum seen in the AAF type G-3 (figure 65a and b). The functional parts remain the same, five appropriately placed bladders. The G-3 suit weighs about 2 pounds, can be folded to fit into a small bag, can be quickly put on or taken off, and may be left in the plane or worn during alerts.

The pressure source is the positive side of the vacuum instrument pump, designed to keep the rotors of the turn and bank and other indicators running by suction (see figures 65c and d). Originally its output was waste; today this output runs de-icer boots (not in fighters), pressurizes jettisonable gasoline tanks to prevent vapor lock (P-47 and P-51 only), and also operates the type G series suits.

The pressure output is metered to the suit in accord with the amount of force applied at a rate between 0.5 and 1.0 pound per G. This means that at 5 G the suit will be pressurized to the extent of 2.5 to 5.0 pounds. The broad range may be surprising; it is based on the fact that the exact pressure required to obtain adequate protection is not critical. The valve which meters the pressure (G-2 valve) is entirely mechanical, weighs only 1-½ pounds, and has a special port for pressurizing jettisonable gasoline tanks, if needed.

Installation in standard fighter aircraft is a 1- to 2-hour job for three men. All the material added to the aircraft weights less than 5 pounds. Once installed, the system requires virtually no maintenance.

Figure 65a.—The G-3 suit is worn over uniform trousers under flying clothing, or next to skin under summer flying suit. Lacings are adjusted to fit, and suit zips on or off.

Figure 65b.—The wide inner belt of the G-2 suit applies pressure to the abdomen under G.

Figure 65c.—Operation of suit is automatic after it is plugged into its pressure line.

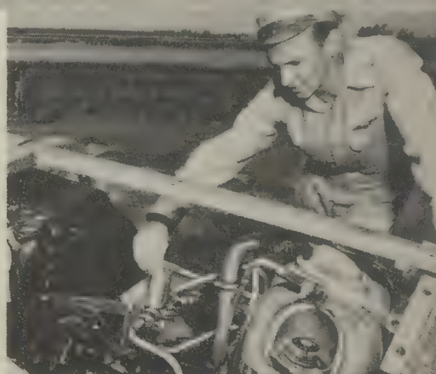


Figure 65d.—Pressure to operate the G-type suit is supplied by the vacuum instrument pump. Weighted valves automatically pressurize suit under G, at rate of 0.5 to 1.0 lb per G.

The Degree of Protection Gained.—On the centrifuge the type G suits make 1 to 1.5 G difference in the level at which the subject blacks out. Translated from the relaxed centrifuge subject to the alert pilot, protection is sufficient to virtually eliminate even graying of vision at levels up to 8 G. At first, it was feared that the protected flyer might tend to pull the wings off his aircraft because of the loss of the warning grayout, but experience has shown that this fear is without foundation. Perhaps this is because the "seat of the pants," that is, perception of weight on the buttocks, weight of feet, and pull down on cheeks, is a more commonly used indicator and, considering the effect of fear on tolerance, a more reliable one. Perhaps it is due to the method by which G is "pulled" in aircraft: the flyer has about 4 seconds of clarity before the force affects him. He can, if he has sufficient speed, snap the aircraft to any G of which it is capable in that time. Hence, if he is going to pull the wings off, he can do it despite the wearing of a G suit, and whether or not he blacks out. Because of the high speed-stall characteristics of high wing-loading aircraft, if the pilot pulls his G slower than his 4 seconds of clarity, he will probably have difficulty reaching degrees of force which will endanger the plane structure.

CHAPTER X

PARACHUTE ESCAPE

In wartime many things may happen to an airplane at high altitude which compel the flyer to abandon his plane. Fire, a crumpled wing, or severe damage inflicted by enemy gunfire may cause an immediate necessity for bailing out, without time for the airplane to be taken to lower altitude. Riding the plane down, even if there is time, is not always feasible, since structural strain may collapse parts of the aircraft, causing the pilot to lose control and adding to the difficulty of the crew's escape. Thus, it is often necessary to leave the plane at altitudes at which oxygen must be used.

Figure 66.—Emergency oxygen cylinder assembly, type H-1. The flow of oxygen is turned on by a manually operated valve and delivered to the mouth through a pipestem.

Emergency Oxygen Bottles

Two types of emergency oxygen equipment are available for use by flyers in emergencies: the bailout bottle and the "walk-around" assembly.

The bailout bottle, which has been designed to be carried in a pocket on the flying suit, is a small, high pressure oxygen bottle for use by flyers who have to bail out above 30,000 feet. The first bailout bottle developed, known as the H-1 (figure 66), supplies oxygen through a pipestem which is placed between the teeth. The revised version, type H-2, (figure 67) directs the

Figure 67.—Emergency oxygen cylinder assembly, type H-2. The flow of oxygen is started by a rip-cord and delivered directly to the mask.

oxygen into the mask so that the mask need not be removed when the emergency oxygen cylinder is used. This feature is an important improvement since the mask affords added protection from the severe cold at high altitudes. The jumper using the H-1 cylinder may protect his face from the cold; however, by not removing his mask and inserting the pipestem under the chin margin of the mask and into his mouth. The H-2 bottle contains 10 percent more oxygen than the H-1. Both are long, narrow bottles (two inches in diameter and eight inches long) and heavy for their size. They are readily distinguishable from the walk-around bottle which is short and thick, like a football, and light for its size. The flow of oxygen from the H-2 bottle is started by a rip-cord type of valve. In the H-1 assembly, a screw valve is used to start the flow.

Figure 68 illustrates the free flow of oxygen into a demand mask at the rate that would be required to keep a man conscious during an open parachute descent, after a difficult escape from a plane at an altitude of 42,000 feet; the data for this figure are based on simulated descents in the decompression chamber. The upper limit of safety with the use of the H-2 cylinder in a difficult escape is about 35,000 feet if the temperature of the cylinder is −40°C (−40°F), or 37,000 feet if the temperature of the cylinder is 20°C (68°F). If escape from the airplane involves very little work, the H-2 bottle is adequate for open parachute descent from 40,000 feet. The cylinder is designed to produce the highest flow rate during the first minute after the rip-cord valve is opened, and a progressively decreasing rate of flow during the remaining nine minutes of its duration. The rate of flow during the first minute is 10.47 liters per minute at a temperature of 25°C (77°F), or 7.67 at a temperature of −47°C (−53°F); during the seventh minute the figures are, respectively, 1.96 and 2.07 liters per minute (figure 69). The rate of flow is a direct function of the pressure of oxygen behind the orifice. Both the pressure and the orifice are affected by temperature, however, so that reduction in temperature decreases the flow. For instance, the pressure drops from 1,800 to about 1,300 psi if the temperature is reduced from 25°C (77°F) to −40°C (−40°F).

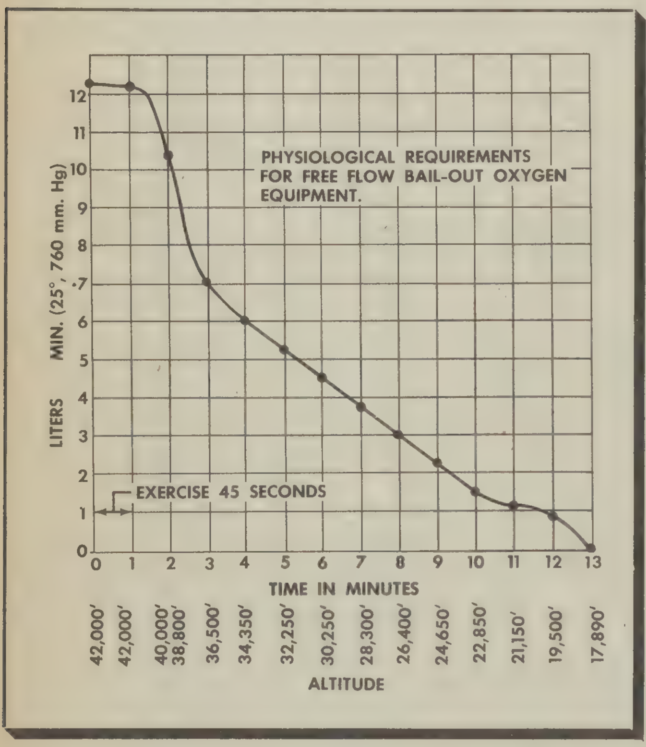


Figure 68.—Rate of oxygen flow into a demand mask required to maintain consciousness during an open parachute descent from 42,000 feet. The flows were determined by simulated descents in a low-pressure chamber. The altitudes are those that would be reached in the elapsed time.

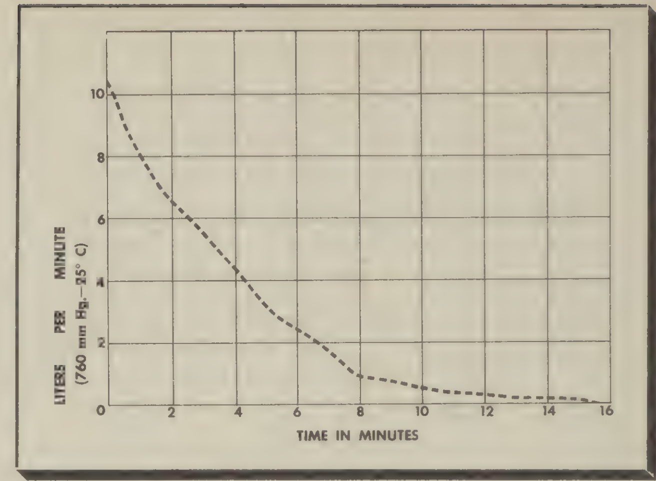


Figure 69.—Rate of flow of oxygen from H-2 bailout cylinder at a temperature of 25°C (77°F).

Each of the bailout cylinders is contained in a sheath and fits into the pocket of the flying suit. It is well to sew the sheath straps to the suit in order to secure the cylinder more firmly in the pocket. The lower straps should be wrapped directly around the thigh; the upper straps are best drawn through the parachute harness which runs under the leg.

A walk-around bottle is provided at each station in multiplace aircraft. It is important for the flyer to understand the different purposes of the two types of emergency oxygen assemblies for escape from aircraft. The walk-around bottle provides the flyer with adequate oxygen to get through the aircraft to the point of exit. If he uses it for this purpose, he may delay the use of his bailout bottle and thereby prolong the duration of oxygen flow during the descent. The walk-around bottle should not be used in place of the bailout bottle during the actual descent.

Advantages of Free-Fall Descent

The rates of descent for both free-fall and open-parachute drops from altitudes of 50,000 feet and lower are

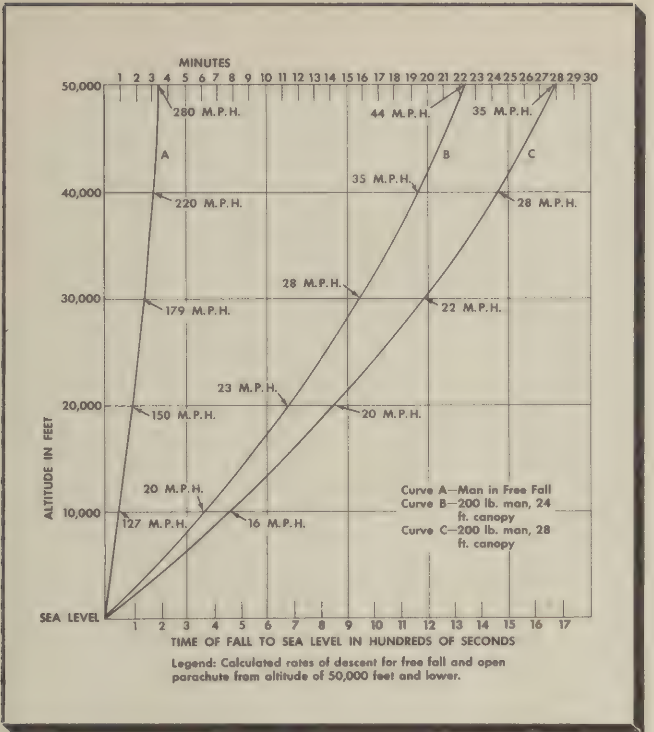


Figure 70.—Calculated rates of descent for free fall and open parachute from altitudes of 50,000 feet and lower.

shown graphically in figure 70. The data apply to a 200-pound dummy. The rate at which the parachutist would strike the ground would be somewhat slower if he weighed less than 200 pounds when fully equipped. There are several advantages to the flyer who falls free, except for the very lowest altitudes (below 1,000 feet). There is no danger of getting the parachute fouled in the aircraft; there is far less shock when the canopy opens; oxygen is required for only a brief time on the way down; the flyer is exposed to the freezing temperatures of high altitude for a much shorter period of time; in the combat zones, a free-falling body is difficult to observe, presenting less of a target to enemy gunfire; and the flyer is in the vicinity of bursting shells for a much shorter time.

The flyer's velocity on leaving the aircraft may be well above the terminal velocity of a freely falling human body. As a man emerges from an aircraft, he is moving with the velocity of the plane. Wind resistance rapidly decreases his speed until the drag impeding his fall is equal to his weight. When this situation has been reached, the man is falling at his *terminal velocity*. The process of slowing to terminal velocity requires only a very short time; 10 or 15 seconds are ample from any speed. Since the velocity required to produce a given drag is greater in the rarified air at high altitude, terminal velocity is greater there than in the denser air at lower altitude.

Measurement of parachute opening shock forces at various altitudes has shown that the forces expressed during opening at high altitudes are much greater than those encountered at lower altitudes. When launching velocities were the calculated terminal velocities for a falling man at each altitude, the force at 7,000 feet was found to be in the range of 8 to 9 G, whereas that at 40,000 feet averaged 33 G. Injuries, sometimes serious, have resulted from the impact of parachute openings, particularly at high altitudes. Figure 71 illustrates the G forces encountered in the impact of parachute opening at various altitudes, as well as the calculated and actual speeds of free-fall and open-parachute descents.

The question of the necessity for oxygen during free falls from various altitudes has been studied by simulated free-fall parachute descents in the low-pressure chamber. The experiments have shown that, with the subject at rest, descent from an altitude of 40,000 feet can be carried out without loss of consciousness and without any supplementary oxygen equipment, if a deep breath of oxygen is taken prior to the start of descent and then is held for as long as 30 seconds. If the breath of oxygen is not taken and held, a brief span of unconsciousness will ensue. In a series of laboratory tests in which loss of consciousness at altitudes of from 30,000 to 36,000 feet was produced during simulated free falls, all subjects recovered sufficiently to pull the rip cord between 25,000 and 2,200 feet, the average pull being made at 14,100 feet. Obviously, oxygen, if available, is a tremendous safeguard.

These laboratory studies have been of limited value, for reports of actual bailouts from altitude show that they are not adequately comparable. The flyer who bails out from an altitude above 30,000 feet will probably experience a period of unconsciousness. But his chance of avoiding it, or at least of shortening its duration, is provided by the use of the bailout bottle during the free fall.

The only known disadvantage of free-fall, as compared to open-canopy descent, is its effect on the ears. If the ears cannot be cleared rapidly during a free fall

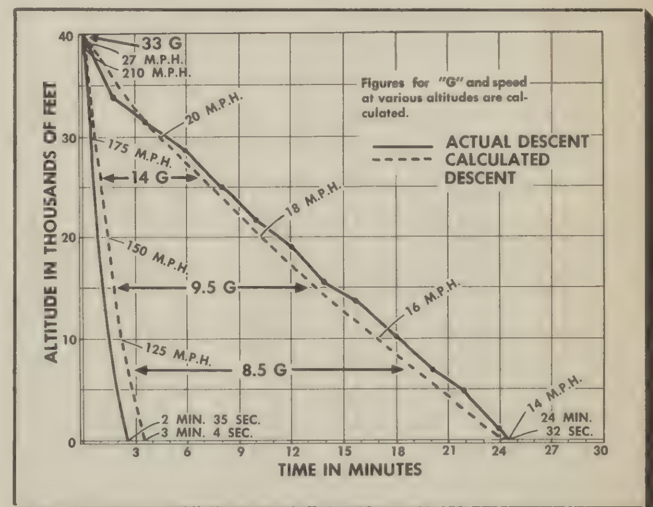


Figure 71.—Free fall and open parachute descent from 40,000 feet and calculated G forces expected in the impact of parachute opening at various altitudes.

at a rate of about 12,000 feet per minute, pain in the ears or actual rupture of the eardrum may occur. Most flyers can clear their ears adequately even while holding the breath for 30 seconds. However, ruptured eardrums are a very minor consideration in comparison with the severe frostbite, gunshot wounds, or impact injury likely to be sustained if the canopy is opened at very high altitude. Since the change in pressure per thousand feet is much greater at low altitude than at high altitude, the danger of ruptured eardrums is reduced if the canopy is opened at 15,000 feet. In a combat zone, if the danger of being strafed is great, it would seem preferable to open the canopy at a lower altitude and risk any damage to the ears which might occur. If the breath is held during a free fall, the nasopharynx should be permitted to maintain ambient pressure. For this reason, it is advisable not to hold the nose closed.

Descent by Open Parachute

If the parachute is opened at an altitude much above 30,000 feet, and the flyer is without oxygen, he undoubtedly will suffer severe and probably fatal anoxia as well as injuries due to the high impact force during parachute opening. If he opens his chute at an altitude lower than 30,000 feet, he may remain conscious without oxygen, but the danger of injury when the chute opens is still very great. In the low-pressure chamber at room temperature, simulated descents have been made from 30,000 feet at an open-parachute rate without loss of consciousness. In an actual escape from a plane, however, the energy expended in leaving the aircraft, the low temperature, and the shock suffered upon opening the parachute have produced more severe anoxia. Under such conditions a man probably would lose consciousness for a portion of the descent, but it is not likely that anoxia would be fatal. In figure 70 are shown altitude-time relationships during descents by open parachute from altitudes of 50,000 feet and lower. Figure 72 shows the average saturation of arterial blood with oxygen, together with the ventilation rates of 13 subjects who performed simulated descents from 30,000 feet by open parachute in the low-pressure chamber. Figure 68 shows the rate of free flow of oxygen, into a demand mask, which is required to maintain consciousness for a difficult escape from a plane, followed by an open-parachute descent from an altitude of 42,000 feet. These data were obtained in experiments conducted in a low-pressure chamber at a temperature of —40°C (—40°F).

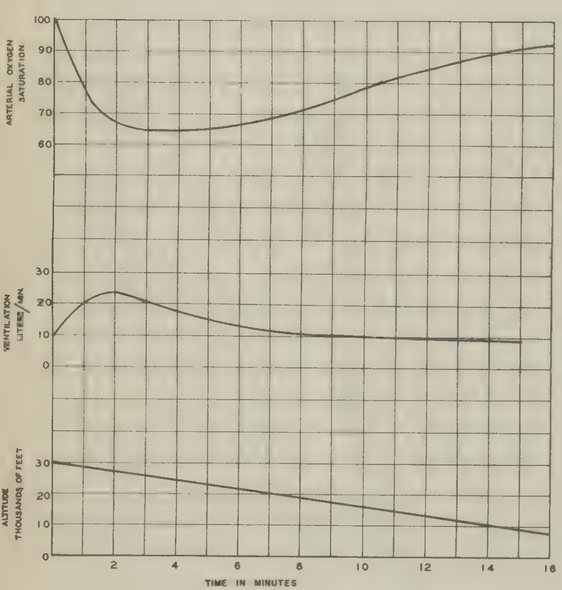


Figure 72.—Percentage of saturation of arterial blood with oxygen, and ventilation rate, compiled from data concerning 13 subjects who made simulated descents by open parachute from an altitude of 30,000 feet, in a low-pressure chamber. (See also the section on respiration in chapter 2.)

Parachute Discipline

PREFLIGHT PARACHUTE CHECK.—A preflight check, which takes less than half a minute, will assure the flyer that his parachute is in proper working order. This check should assure the following: (1) that the parachute has been packed within 2 months (1 month in the tropics) and inspected within 10 days; (2) that the rip cord pins are not bent or rusty and are properly articulated in the cones; (3) that the seal is unbroken; and (4) that the pack and harness appear to be in satisfactory condition.

FITTING OF THE PARACHUTE HARNESS.—Fitting of the harness is a highly important matter. The parachute harness has been designed to permit distribution of the shock load of an opening parachute as uniformly as possible. It accomplishes this task well only if it is properly fitted. A proper fit is a tight fit, so tight, in fact, that it is comfortable only when the flyer is seated. It takes only a minute to fit a harness properly before take-off, and that short time proves its value the day the flyer has to use his parachute.

CLEARING THE AIRPLANE.—It is doubtful that there ever have been or ever will be two emergency parachute escapes exactly alike. The difficulty encountered in leaving the plane, the time available, and the mental and physical condition of the jumper are all variables of importance. The time and effort required to get from a station to an escape hatch in an airplane depend upon the following factors: (1) the station, (2) the type of airplane, (3) the stability of the airplane in flight, (4) the position of the airplane, (5) the size of the man, (6) the type of clothing worn, (7) the type of parachute worn, (8) the physical fitness of the man, and (9) the training of the man in escape procedure.

It is during the time required to go from station to exit that the most critical need for oxygen exists. If a flyer should lose consciousness from lack of oxygen before clearing the airplane, it is doubtful that he would ever get out. Without oxygen a man has from 1 to 1½ minutes of useful consciousness at 30,000 feet, if he is at rest. The duration of consciousness would be lessened by the activity entailed in reaching the bailout exit.

ATTITUDE ON LEAVING THE PLANE.—Since the flyer is likely to incur more serious injury if his head, rather than his feet, strikes the aft end of the hatch through which he falls, the jump should be made, whenever possible, by rolling out head first from the aft end of the hatch. If the jumper kneels and falls forward from the rear edge of the hatch, he doubles the useful length of the opening, for he falls through the space from back to front and then from front to back as the airplane travels forward during his initial fall. If he is compelled to go out from the front end of the hatch, the flyer should try to pivot out from a sitting position, placing his hands on the aft edge for support. His arms should be kept in front of him, against the aft end, to protect his head as he falls through. As soon as he has cleared the exit hatch, he should straighten his body and legs, simulating the position of attention.

Some flyers prefer to leave the plane feet first. Though this method may be suitable if the hatch is large and there are no projecting parts of the airplane behind the point of exit, the standing jump is dangerous if the hatch is small or a door is used as the bailout exit. If the stand-up drop is used, it is important that the arms be held close to the rigidly extended body and the legs together. The body should be kept in a straight line and the head should be held upright, for looking downward encourages "jack-knifing" and somersaulting. In other words, the parachutist who emerges from a plane feet first should do so in the position of attention—head straight, gaze forward, arms close to the body, and legs together.

The *position of the hands* on leaving the plane is important. Even an experienced parachutist will pull his rip cord as he emerges from the plane if he jumps with his hand on the rip-cord handle, since there is a moment of mental chaos as one makes the plunge. If the flyer grasps the harness near the rip cord with his hands when he jumps, he will have no difficulty in finding the rip cord later. He will recover his presence of mind in time to fall free as far as is reasonable under the circumstances. *The elbows must be kept close to the body* at all times as the air stream at high speeds may make the limbs difficult to control if they are not held in the proper position.

ATTITUDE WHEN RIP CORD IS PULLED.—Though it is impossible for the inexperienced jumper to control his free-falling position with relation to the ground, he can control his attitude in flight. The posture of the flyer's body when the rip cord is pulled is important if injury from the opening shock is to be avoided. The body should be extended, legs and thighs together, and arms close to the body as during the free fall. When the moment comes for pulling the rip-cord handle, the rip-cord pocket should be grasped with the left hand and the handle should be grasped with the right hand and yanked. The flyer should look down at the rip cord as he pulls it. He should under no circumstances watch the canopy open, as his head will be jerked backward violently. The head should be held forward firmly with the chin on the chest until the canopy is fully opened. Then the canopy should be examined visually for thrown lines and twisting. Thrown lines are tangles of the shroud lines which prevent certain portions of the canopy from opening. They can be untangled best by jerking sharply on several lines at a time. The lines can be reached by pulling down with both hands on the left or right riser. Twists of the shroud lines result if the body makes a twisting movement when the canopy opens. They usually will correct themselves without aid from the flyer. If they seem stable, they can be released by a scissors kicking motion of the legs from the hips, as in swimming side stroke. This movement can be practiced on a simple pivoted trapeze bar 8 or 9 feet off the ground. The body should be suspended by means of the hands so that the body and the bar can be rotated by the scissors kick.

PREPARING FOR THE LANDING.—When landing, the jumper should face downwind, so that impact will find him drifting forward. He may use the body turn to accomplish this. To turn to the right, the right hand reaches behind the head and grasps the left risers, while the left hand reaches in front of the head and holds the right risers. The degree of turn to the right may be regulated by the amount of pull. A left body turn may be accomplished in exactly the opposite way, left hand behind the head pulling on the right risers, right hand in front of the head pulling the left risers.

ATTITUDE IN LANDING.—If the parachute is opened at low altitude after a free fall the most common cause of injuries is landing shock. Most of these injuries are avoidable if the flyer knows the proper landing technic. The legs should be held close together at the knees and ankles. The body should be flexed slightly at the hips and knees so that the legs are slightly forward of the body. The soles of the feet should be parallel with the ground (figure 73). The chin should be held rigidly on the chest just as it is when the canopy opens. The ground must be watched closely, but it is better to watch it at an angle of 45 degrees than to look straight down. The arms should be raised, gripping the shroud lines. At the moment of contact with the ground the muscles should be in tone, neither relaxed nor rigid. By going into a roll on the ground, the flyer can reduce the intensity of the shock. The roll must be down the side of the body, not flat on the face or back, and the legs must not be separated until the roll is completed.

GETTING OUT OF THE HARNESS.—Removal of the harness presents a problem only if the landing is in a wind, when the canopy can drag the parachutist quite rapidly over the ground. He should roll over on his

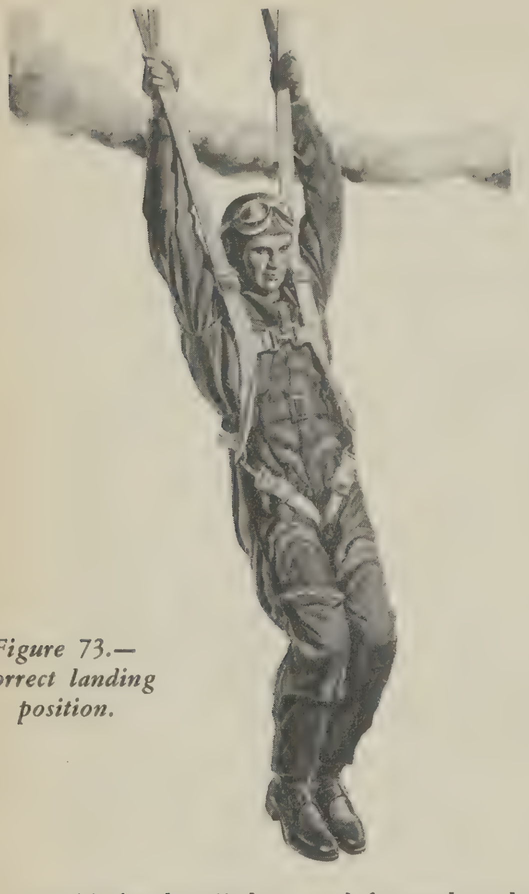


Figure 73.—Correct landing position.

back, keep his head pulled up and forward, and with both hands release his leg strap buckles one at a time. The breast strap then can be released and one arm slipped out. If the other arm is then raised, the canopy will drag the harness away from the body.

LANDING IN TREES OR WATER.—Landings in trees or water present special problems. When coming down in a tree, the flyer must keep his thighs and feet together and he may or may not be completely flexed in a ball. The arms must be folded with the head forward, buried in them. With the body in this position, the eyes and face will be protected from small branches and the crotch protected from large ones. The canopy usually will lodge in the branches and suspend the flyer safely in the tree. If help is available, it is better for the flyer not to try to free himself from the harness as he may be injured severely if the canopy becomes dislodged because of his movements.

Landings in water have been accomplished in various ways. The flyer should not try to judge his distance from the water or get out of his harness before hitting the water. His judgment of distance is too unreliable. There are many horror stories of men being drowned because of the canopy, but if anyone has drowned after landing in water, it was because of *panic* and not because of the canopy. Unless the air is absolutely still, the canopy will not come down over the flyer. Furthermore, if he inflates his Mae West life vest in order to keep him afloat, he has plenty of time to get out of the harness and free of the lines and canopy. Above all he should not get panicky; he should work slowly and carefully, get clear of the rigging, and then open his emergency equipment. If possible, it is good practice before reaching the water to release the chest strap and slide back on the seat strap. The thigh buckles then can be released before striking the water, but the danger of falling out of the opened harness is probably greater than that of not being able to get out of a buckled harness in the water. In the water, while regulating the Mae West and releasing the leg straps, it is well to remain upstream and away from the canopy and shrouds, in order to avoid entanglement in them. The Mae West should never be inflated until the chest strap is unfastened.

The following is a story told by an Army pilot about his emergency escape from a P-47 at 32,000 feet:

When the plane which I was testing reached 38,000 feet, I half-rolled it into a dive. About 2,000 feet below the starting point of the dive, I noticed an excessive amount of smoke in the cockpit, and when the stick apparently broke, I realized that there must be a fire in the tail of the airplane. Deciding to bail out, I turned the emergency valve of my oxygen regulator so that I would be breathing pure oxygen until I left the ship, freed the canopy of the cockpit, and unbuckled my safety belt. I did not attempt to level off the plane or cut the engine, as I thought it would be better to keep the ship in a steady dive at full power rather than to have it change direction and roll over on its back as I jumped. I planned the procedure I would follow to avoid hitting the tail and then climbed out of the cockpit on the left side. As I left the cockpit, the hose on my A-14 mask stretched, pulling the mask off my face about 3 or 4 inches, then broke at its connection to the mask. As I left the airplane, I noticed that the airspeed was 300 mph and the altitude 32,000 feet. I observed a lot of smoke coming from the supercharger outlet, and that was the last I saw of the plane.

I realized that at this altitude, temperature, and speed, I had better not open my parachute as I would probably freeze to death, die from lack of oxygen (since I had no bailout bottle), or tear myself or my chute apart when the chute opened. I decided to delay opening the chute for as long as I could hold my breath. I began to spin very rapidly, face up and parallel to the ground, and continued to fall this way. When I knew that I could hold my breath no longer, I decided that I would open the parachute when I felt that I was about to lose consciousness. When I pulled the rip cord, the chute opened with a terrific jerk, I felt a sharp pain in my back and also on the inside of my right thigh, since the right leg strap took the whole load. I looked up and saw that my chute was open but that the shroud lines were twisting because of the way in which I had been spinning. My hands were becoming very cold and I placed them under my arms. The last thing I remember as I passed out at approximately 27,000 feet was that the canopy on my chute was almost closed.

I regained consciousness at approximately 8,000 feet. I felt very bad, my leg was very painful, my eyes were frozen and it seemed as though I were looking through tissue paper. In a short time my eyes cleared and I could see as well as ever. My chute was fully open and I was swinging in an arc of approximately 20 degrees. The pain in my back did not seem particularly bad, probably because my leg hurt so much. Later I learned that I had sustained a fracture-dislocation of my first and second lumbar vertebrae. I did not have enough strength even to lift my arms. I realized that this probably was due to my anoxic condition and thought the best thing I could do was to relax as much as possible and try to regain my strength. When I reached approximately 5,000 feet I could raise my arms but decided I had better save my strength again in order to be able to "slip" my chute in case I was going to hit a tree or house in landing. I landed in a large pasture and collapsed like a wet rag when I hit the ground. It had taken me approximately 16 minutes to get down after leaving the airplane.

CHAPTER XI

NOXIOUS GASES IN AIRCRAFT

Changes in the composition of air in cockpit or cabin during flight, as a result of contamination by gases or fumes, may lead to profound physiological effects. Several accidents have been attributed directly to intoxication of flying personnel by noxious fumes, and in many the evidences has been strongly in favor of extraneous gases as the causative factor.

Contamination of the atmosphere in aircraft compartments may result from exhaust gases, gasoline vapor, hydraulic fluid vapor, coolant fluid vapor, oil fumes, or poison gas.

Exhaust Gases in Aircraft Compartments

The amount of exhaust gas reaching aircraft compartments fluctuates because it is diluted with atmospheric air before it enters. One of the most important factors in determining the concentration of exhaust gas in aircraft compartments is the position of the latter in relation to the engines. The situation is potentially most dangerous when the cockpit is situated directly behind an engine, as in single-motored or tri-motored aircraft. Little difficulty has been experienced with two-motored or four-motored aircraft. When an engine is located immediately in front of the cockpit the amount of exhaust gas entering depends largely on the manifold system. The worst condition is encountered with engines having short exhaust stacks. In one type of airplane, which had given difficulty for years, it finally was found that the fumes were entering an opening at the extreme rear of the aircraft, where the tail wheel emerged. The fumes then travelled forward in the fuselage, causing a dangerous concentration of carbon monoxide in the atmosphere about the pilot. Closing the tail wheel opening with a boot eliminated the difficulty at once. This experience indicates that the exhaust gases should be discharged at a distance from the slipstream which immediately surrounds the fuselage. When this is not practicable, all openings in the fuselage and fire wall should be closed.

There is also evidence to indicate that liquid-cooled single-engine types of aircraft are less likely to be contaminated by exhaust gas than are air-cooled radial-engine airplanes.

Another way in which contamination of aircraft compartments may occur is through the escape of carbon monoxide from cabin heaters which ultilize exhaust gases as a source of heat. Finally, during combat operations, it is considered possible that the effects of enemy gunfire, not necessarily terminating flight, may open exhaust collector rings and holes in the fuselage and fire wall, causing dangerous concentrations of gas in the cockpit.

The composition of exhaust gas varies widely, depending largely upon the grade of aviation fuel and the fuel: air ratio at which the engine is operated. Carbon monoxide, methane, and hydrogen are formed as a result of the incomplete combustion of fuel. As the fuel: air ratio decreases and the completeness of combustion increases, the percentage of carbon dioxide in the exhaust gas rises, with a corresponding decline in the percentage of carbon monoxide. Conversely, as the mixture became richer, the carbon monoxide content of exhaust gas increases. With fuels containing xylidine, the oxides of nitrogen also appear in the exhaust gas, the amounts varying with xylidine concentration and fuel: air ratio. Further discussion of exhaust gases will be limited to those, practical physiological significance, specifically carbon monoxide and nitrogen oxides.

CARBON MONOXIDE.—Carbon monoxide is the most important indicator of the presence of exhaust gas, because it is the principal toxic constituent of exhaust gas and because it is most easily measured. Carbon monoxide normally occurs in the exhaust fumes of aircraft engines as a result of the incomplete combustion of carbonaceous material. The amount varies considerably, depending upon the octane rating of the fuel, the fuel:air ratio, the throttle setting, and the altitude, and it extends over a range of from 1 to 7 percent, with an average of 2.8 percent.

Poisoning by inhalation of carbon monoxide, fortunately, is a comparatively rare occurrence in aviation. The potential danger, however, is great enough to require attention, especially since the toxicity of carbon monoxide is increased by any reduction in the partial pressure of oxygen in the lungs. Concentrations of carbon monoxide, which are of little importance at ground level, may become dangerous at high altitudes. The deleterious effects of carbon monoxide result from its dual action on the blood, by means of which it produces anoxia. Carbon monoxide combines with hemoglobin in a manner similar to that of oxygen; however, the affinity of hemoglobin for carbon monoxide is more than 200 times greater than its affinity for oxygen, so that in the competition for a place in the hemoglobin molecule, the odds are more than 200 to 1 in favor of carbon monoxide, to the exclusion of oxygen. In addition, carbon monoxide in arterial blood increases anoxia further by preventing liberation of oxygen from the blood to the tissues. Hence, the extraordinary intensity of anoxia caused by the combination of carbon monoxide with a given proportion of hemoglobin is explained.

The blood saturation attainable with various concentrations of carbon monoxide in the inhaled air and the resultant effects are shown in figure 74. Headache is one of the first symptoms to appear and always should be considered a warning sign.

The subjective symptoms resulting from dangerous concentrations of carbon monoxide are throbbing head-

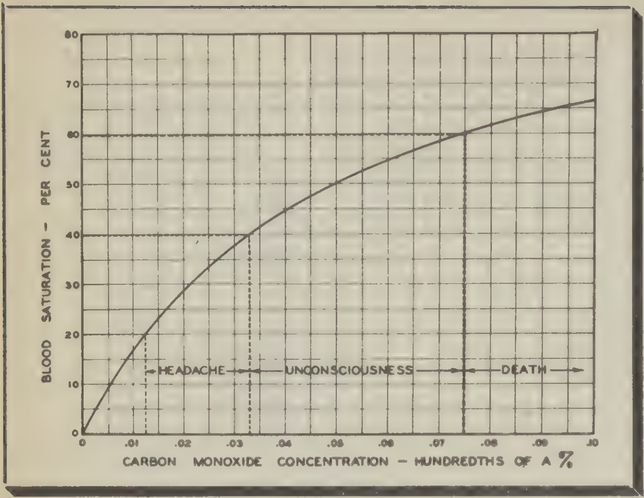


Figure 74.—Saturation of the blood with carbon monoxide and resulting symptoms produced by various concentrations of carbon monoxide in the inspired air.

TABLE 9

SYMPTOMS WHICH DEVELOP AT VARIOUS CONCENTRATIONS OF CARBON MONOXIDE IN THE BLOOD

Carbon monoxide, percent in blood	*Symptoms*
0 to 10	None
10 to 20	Tightness across forehead, possibly slight headache, dilatation of cutaneous blood vessels.
20 to 30	Headache, throbbing in temples.
30 to 40	Severe headache, weakness, dizziness, dimness of vision, nausea and vomiting, and collapse.
40 to 50	Same as previous, with increased pulse rate and respiration, and more possibility of collapse.
50 to 60	Syncope, increased respiration and pulse, coma with intermittent convulsions, Cheyne-Stokes' type of respiration.
60 to 70	Coma with intermittent convulsions, depressed heart action—possibly death.
70 to 80	Weak pulse and slowed respiration, respiratory failure and death.

TABLE 10

DANGEROUS CONCENTRATIONS OF CARBON MONOXIDE

Concentration, percent	*Effect*
0.01, or 1 part in 10,000	No symptoms for 2 hours
0.04, or 4 parts in 10,000	No symptoms for 1 hour
0.06 to 0.07, or 6 to 7 parts in 10,000	Headache and unpleasant symptoms in 1 hour
0.10 to 0.12, or 10 to 12 parts in 10,000	Dangerous for 1 hour
0.35 or 35 parts in 10,000	Fatal in less than 1 hour

ache, usually localized postorbitally, nausea, dizziness, and dimming of vision. These symptoms vary with the carbon monoxide content of the blood, as shown in table 9. Table 10 shows the effect produced by breathing various concentrations of carbon monoxide in air at ground level. A concentration of 0.04 percent is required to produce the first symptoms.

The symptoms which occur during flight are governed by four principal factors: (1) concentration of carbon monoxide in the inspired air, (2) duration of exposure, (3) altitude, and (4) respiratory minute-volume (which depends on the activity of the flyer). An increase in any or all of these factors causes an increase in severity of the symptoms. The effects of carbon monoxide on arterial saturation at various altitudes are shown in figure 74. Assuming that dangerous effects of oxygen want become manifest at an arterial hemoglobin saturation of 80 percent, figure 75 shows that, with no carbon monoxide in the air, the saturation point is reached at 14,000 feet. A similar condition occurs at 11,000 feet when the concentration of carbon monoxide is 0.005 percent, and at 7,000 feet when the concentration is 0.01 percent. Thus, as little as 0.01 percent carbon monoxide can lower the altitude tolerance to half what it would be if only pure air and no carbon monoxide were present.

Figure 76 shows the relation between altitude and time of breathing carbon monoxide required to reduce the arterial oxygen saturation to 85 percent. When the demand oxygen system is in use the effects of altitude on tolerance to carbon monoxide will be reduced because of the added oxygen (figure 77). The two curves for sea level conditions and 5,000-feet equivalent are not duplicated exactly by any demand regulator, however the AN6004-1 diluter demand regulators will maintain blood saturations between ground level and 5,000-feet equivalent.

The only logical method of eliminating the menace of carbon monoxide is to prevent it from entering the cabins and cockpits of aircraft. The onset of carbon monoxide poisoning is so insidious and its effects are so disastrous that only preventive measures are reliable.

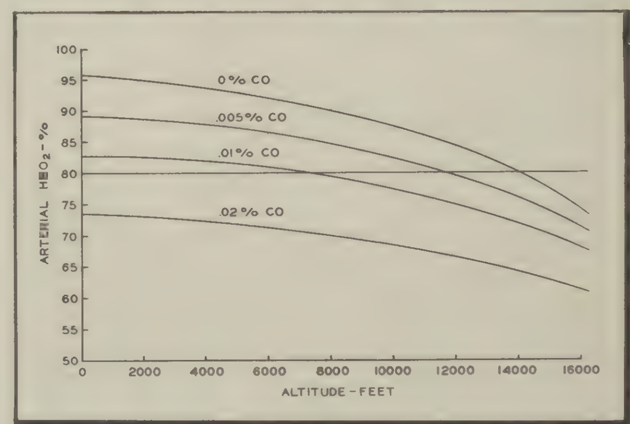


Figure 75.—The effects of carbon monoxide on hemoglobin in arterial blood at various altitudes.

Although it is desirable that no carbon monoxide be present in aircraft, this is often difficult to accomplish in single-engine airplanes. In this situation it is necessary to establish the allowable concentration which is harmless and which can be measured by practical methods. The maximum permissible concentration in personnel compartments of AAF aircraft has been established at 0.005 percent.

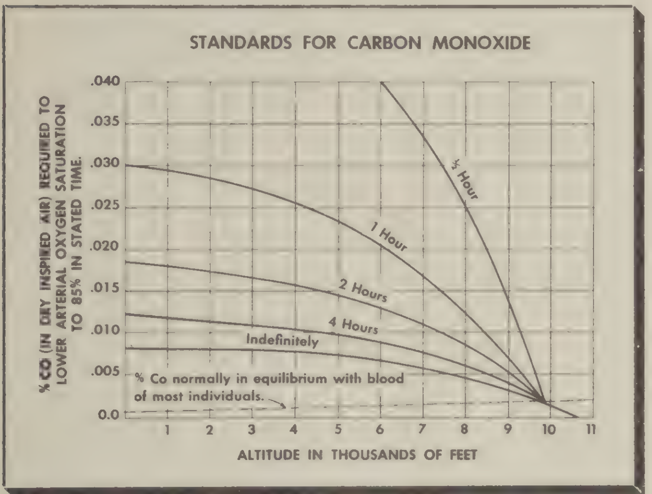


Figure 76.—Percent of carbon monoxide (in dry inspired air) required to lower arterial oxygen saturation to 85 percent in stated time. In this graph respiratory rate is assumed to be 10 liters per minute. Data calculated from laws governing the equilibria of oxy-, carboxy-, and reduced hemoglobin in the presence of known partial pressures of oxygen and carbon monoxide using K-210. (From Handbook of Respiratory Data in Aviation, National Research Council.)

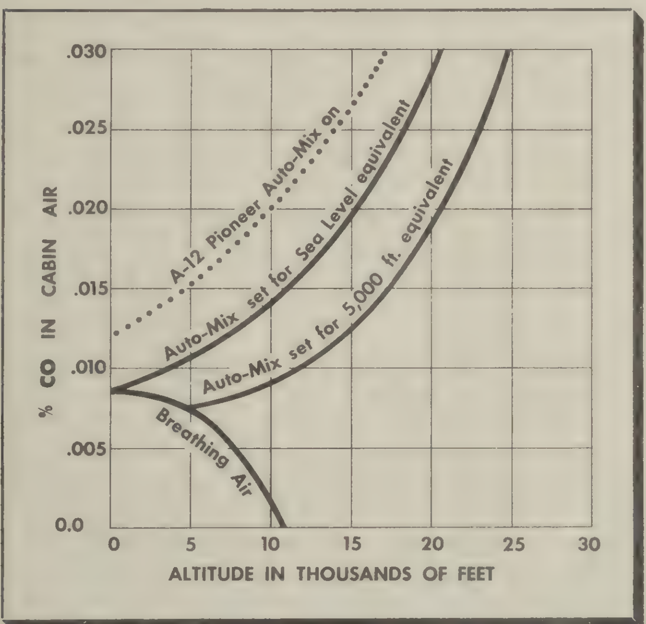


Figure 77.—Percent of carbon monoxide in cabin air required to bring arterial oxygen saturation to 85 percent at equilibrium. The curve for the AN 6004-1 regulator would fall between that for sea level and 5,000 feet equivalent. (From Handbook of Respiratory Data in Aviation, National Research Council.)

All new aircraft models must meet rather rigid specifications for freedom from contamination by carbon monoxide before they are accepted by the AAF. However, planes which were originally free from contamination, or contained only slight amounts of carbon monoxide in the initial tests may deteriorate from wear, or change as a result of structural modifications introduced while they are in service. Periodic tests will reveal such contamination and serve as a check on the adequacy of maintenance.

Dangerous concentrations of carbon monoxide in aircraft compartments are indicated by the subjective symptoms already discussed and by the odor of exhaust gases. When the existence of carbon monoxide is suspected, tests should be made to establish its presence so that corrective measures may be initiated immediately. The following tests may be used: (1) analysis of blood by the Van Slyke, or Roughton-Scholander methods, or by the use of the AML Blood Carbon Monoxide Analyzer, (2) analysis of air by a method devised by the National Bureau of Standards, and involving the colorimetric determination of a percentage of carbon monoxide in a sample of cockpit air passed through a tube which contains a gel impregnated with an indicator (Type C-40655, Carbon Monoxide tester, spot check /NBS Tubes/).

The subjective symptoms of carbon monoxide poisoning are similar to those of oxygen lack. Upon the first appearance of symptoms, the canopy should be opened if possible to eliminate the gas by ventilation. The concentration of oxygen breathed should be increased to 100 percent by turning the auto-mix of the demand oxygen regulator to the "OFF" ("100 percent oxygen") position. At altitudes above 30,000 feet, carbon monoxide can enter the lungs only through a mask leak, since the regulator delivers 100 percent oxygen with the auto-mix in either the "ON" or "OFF" position. Carbon monoxide poisoning may be distinguished from anoxic anoxia by the characteristic red flush on the face and by pink fingernails. In anoxia from lack of oxygen, the fingernail beds and face become cyanotic. The treatment for carbon monoxide poisoning, either in flight or on the ground, is rest and administration of 100 percent oxygen. When pure oxygen is breathed, the elimination of carbon monoxide takes place at a rate several times greater than that occurring when ordinary air is breathed. Carbon dioxide-oxygen mixtures have been used but are now considered dangerous especially when the respiratory center is depressed (TB Med. 131, Jan 45).

OXIDES OF NITROGEN.—The oxides of nitrogen, present in exhaust gas when aviation fuel which contains xylidine is burned, include nitrous oxide, nitrogen oxide, nitrogen dioxide, and nitrogen tetroxide. Nitrogen dioxide is the most important of these from the point of view of toxicity. The small concentrations of nitrous oxide and nitrogen oxide which are formed by the com-

bustion of nitrogenous materials are too slight to produce harmful effects.

When nitrogen dioxide is inhaled at body temperature, 70 percent of it is altered at once to nitrogen tetroxide which reacts with water to produce nitric and nitrous acids. These acids may account for irritations of the mucous membranes of the eyes and upper respiratory tract which follow continued exposure to fumes of nitrogen oxides. The principal symptoms of nitrogen dioxide intoxication are vertigo, headache, nausea, tightness in the chest, and cough.

The oxides of nitrogen are usually represented quantitatively in terms of the amount of nitrogen dioxide present. Concentrations up to 0.06 percent of this gas appear in exhaust mixtures when the xylidine content of the gasoline is 1 percent. Higher concentrations of xylidine in the fuel result in higher concentrations of xylidine in the exhaust. A definite relationship also exists between the formation of nitrogen oxides and the fuel:air ratio. In contrast to the formation of carbon monoxide, however, high fuel:air ratios result in the smallest concentrations of the oxides of nitrogen and vice versa.

The oxides of nitrogen, more toxic than carbon monoxide, actually are present in much lower concentrations in exhaust gas than is carbon monoxide. If the contamination of air by carbon monoxide is controlled sufficiently to prevent harmful effects, adequate precautions will have been taken to prevent injurious effects from nitrogen oxides.

Miscellaneous Gases*

GASOLINE VAPOR.—Aviation gasoline is a complex fuel consisting of a mixture of aliphatic and aromatic petroleum hydrocarbons and special additives such as tetraethyl lead and xylidine, in varying proportions. One gallon of gasoline, completely evaporated, will form approximately 30 cubic feet of vapor at sea level. Since these vapors are heavier than air and are readily absorbed in the lungs, their toxicity is of practical importance. Several instances have been reported in which untoward reactions have occurred among flying personnel who have been exposed to volatilized gasoline.

Even one-tenth the concentration of gasoline vapor required to support combustion or form an explosive mixture is harmful if inhaled for more than a short time, and will cause dizziness, nausea, and headache. If the concentration is high, absorption by the lungs may be extremely rapid, leading to the appearance of symptoms after only a few minutes of exposure. Large amounts act as an anesthetic and cause unconsciousness. Acute poisoning is marked by burning of the eyes and lacrimation, as well as by severe effects upon the centrol nervous system, manifested by restlessness, disorientation, disturbances of speech, vision, and hearing, convulsions, coma, and death.

The maximum safe concentration in exposure to ordinary gasoline vapors is 0.05 percent, or approximately 500 parts per million. Aviation gasoline is at least twice as toxic because of its contents of aromatic hydrocarbons. Because of the precise and frequency complicated activities required of flying personnel, even small amounts of gasoline vapor in aircraft must be considered dangerous. The hazard in the inhalation of these fumes constitutes only a part of the total danger, however, for they may also be responsible for the occurrence of fires and explosions in flight.

Tetraethyl lead, the dangers of which are well known, is also absorbed in the lungs. However, the amount of tetraethyl lead provided by the various specifications of aviation fuel is such that it is relatively free of harmful effects through the inhalation of gasoline vapor. This hazard has manifested itself only under especially bad conditions of handling the fuel, as when gross spillage has occurred in a confined space.

Little is known concerning the systemic effects of xylidine on humans, but animal experiments have indicated that this substance is highly toxic. Frequent exposure to xylidine is probably hazardous, but the danger of xylidine poisoning from a single exposure to aviation gasoline vapor appears remote.

HYDRAULIC FLUID VAPOR.—The occupants of military aircraft may be exposed to hydraulic fluid and its vapor through an escape of such fluid due to failure of the hydraulic system, or a break in the hydraulic lines caused by enemy gunfire. Frequently the odor of the fluid is barely detectable and no toxic effects occur. On the other hand, a small leak from an hydraulic pipe or gage under pressure may give rise to a fine spray of fluid which quickly diffuses throughout the cockpit, or a larger leak may result in the accumulation of a pool of liquid on the floor. In either case the cockpit air may soon attain a high degree of saturation with the volatile constituents of the hydraulic fluid, leading to serious toxic effects upon the occupant.

Of the two types of hydraulic fluid currently used by the AAF, that with a petroleum base is used in all combat aircraft, with the exception of the P-40, and in multiengine cargo airplanes. This type of hydraulic fluid contains substances which have low volatility and toxicity. The type with a castor oil base, used in the P-40, in single-engine cargo aircraft, and in most training planes, presents greater potential dangers, for its volatile constituents, especially butyl cellosolve ethylene and propylene glycol, and octyl and isoamyl alcohol, are toxic when inhaled. The alcohols produce a narcotic effect about 12 times greater than that of ethyl alcohol, and in addition, they may produce headache, vertigo, and irritation of the eyes and upper respiratory tract. The symptoms resulting from the inhalation of butyl cellosolve vapor include headache, vertigo, and impairment of vision and judgment.

The following excerpt is taken from an aircraft accident report and will serve to illustrate the dangerous effects which may result from exposure to hydraulic fluid vapor in flight:

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*Abridgement of reports from Medical Safety Division, Office of Flying Safety.

After about an hour's flying as a member of a formation flight, the pilot began to have trouble. He noticed some dimness of vision and had difficulty in seeing the lead plane. He rapidly became weak and dizzy. He opened his canopy, thinking some fresh air would make him feel better. No improvement occurred. At this time he noticed some mist in the lower part of the cockpit and saw some fluid spraying up from the region of the equalizer valve. Thinking that he was going to lose consciousness, he pulled away from the formation and decided to leave the plane. He experienced difficulty in loosening his safety belt because of his hazy mental state and found he was too weak to get up in the cockpit. He managed to roll the plane over on its side and more or less, fell out. Once in the air he experienced difficulty finding the ripcord but finally managed to pull it and open the parachute. He lost consciousness when the chute opened but recovered just before he reached the ground. He felt nauseated for a few minutes after this experience. Physical examination and chemical analysis of the blood for carbon monoxide after the accident were essentially negative.

COOLANT FLUID VAPOR.—Coolant fluid, used in liquid-cooled engines, consists of ethylene glycol diluted with varying amounts of water up to 80 percent, depending on the aircraft model. Although toxic when ingested and fairly volatile, ethylene glycol does not cause any important toxic effects when inhaled as a vapor. Continued exposure to the vapor over a period of months produced no deleterious effects apart from moderate irritation of the respiratory passages. No instances of intoxication from coolant fluid vapor in flight have been reported.

OIL FUMES.—Oil escaping from a break in an oil hose connection and making contact with hot engine parts may lead to the formation of a smoke which reaches the cockpit. Armstrong mentions several cases in which hot fumes were inhaled in flight. The resulting symptoms were similar to those of carbon monoxide inhalation: headache and nausea, in addition to irritation of the eyes and upper respiratory tract. The specific chemical compounds responsible for the symptoms are not known, but they probably include the principal breakdown products of lubricating oil: methyl and ethyl aldehyde, acrolein, and paraformaldehyde.

POISON GAS.—The principal war gases known at the end of the last war are all heavier than air and tend to collect near the ground. They are of importance to flying personnel only on or near the ground. In the event of the necessity for landing an airplane on contaminated terrain, or during a gas attack, the best protection for the occupants of the aircraft is provided, of course, by gas masks. If these are not available, the use of goggles and an oxygen mask, with the auto-mix on the regulator turned to the "OFF" ("100 percent oxygen") position, afford the best protection for the eyes and respiratory tract.

CHAPTER XII

PHYSICAL HUMAN ENGINEERING IN MILITARY AIRCRAFT

Because of increasing operational demands the problems in design and construction of military aircraft and of personal equipment for the occupants have become extremely involved. Certain standard facts are well established in the preliminary design of military airplanes. The sizes of instruments, engine accessories, and control mechanisms are well known, and now enter almost automatically into the considerations of the designers. There is little or no question concerning spatial requirements in the finished airplane which are dictated by these parts. On the other hand, insufficient attention has been devoted to requirements in aircraft design and construction based upon human physical factors. Physical criteria for the design of personal equipment for the flyer have been somewhat better developed.

The importance of an adequately based approach to the physical relationships of the flyer to his personal equipment and his airplane is readily apparent. The successful execution of an aerial mission is dependent upon the performance of the man or men involved in the operation. To maintain a high standard of performance through the media of properly functioning personal equipment and effective execution of physical duties, it is necessary to determine the requirements demanded of equipment and aircraft by variation in the physical nature of flying personnel. Consideration has been given the questions of oxygen availability and consumption, G tolerance, and temperature tolerance in other sections of this book. It is the purpose of this chapter to discuss criteria relevant to personal equipment and aircraft design which originate in size variations of separate portions of the individual anatomy, as well as in the total size of the flyer wearing all his necessary equipment.

Relation of Body Size to Aircraft Design

The aircraft assembly is not complete until proper provision has been made for the last item to go into it, the flyer. The human body is an integral part of the airplane in flight. Failure to recognize the necessity for adequate determination of variations in body size has led to serious difficulties in the function of military aircraft under combat conditions. In one standard cargo aircraft, arranged for troop transport, the design of the bucket seats is such that personnel sitting in them very long suffer discomfort from the unusual pressure on the area in contact with the seat and the position required by the curved contour upon which the back must rest. Aircraft are put into production without adequate regard for the size of the men who may be flying them. Seat adjustments are not adequate. A tall man bumps his head on the canopy, or his knees press into the control panel. A short man, even with the seat at high

adjustment, cannot see well enough to taxi. Catwalks do not permit personnel with complete flying equipment to pass through them.

It is evident that if the size of the human body is to influence the design of aircraft, it is necessary to establish data regarding body sizes of all personnel destined to enter military aircraft under operational conditions. Utilizing this information, specifications on the standardization of body sizes may then be written. These data are obtained through methods similar to those used by an engineer to determine the dimensions of cylinders designed to accommodate a random set of pistons. The distribution of cylinder sizes required to accommodate such pistons can be established by taking certain measurements on the pistons. Using this approach to determine requirements based on the size of the individual, approximately 47 measurements were taken on a series of 3,000 aviation cadets and 600 gunners.

In the operation of aircraft the pilot becomes most intimately associated with the seat and the cockpit. One of the basic requirements of seat and cockpit in aiding efficient operation of the pilot is the proper accommodation of the seat to varying body sizes. Collected data have made it possible to determine the size of the seat and the adjustments which must be built into it and the associated controls in order to obtain maximum accommodation. These data are being applied to new aircraft designs. Conversely, it has been possible to establish certain size requirements for the selection of flying personnel who most satisfactorily meet the requirements of existing designs.

Profile scale manikins are used in the determination of these relationships (figure 78). The manikins represent three standards of body size. Type A is an average of the 3,000 aviation cadets measured and supplies a point of reference. To establish over-all spatial requirements, minimum and maximum values were provided by determining the entire stature range of 600 gunners. The range was divided into equal thirds, and by averaging the men falling in the short one-third and those falling in the tall one-third, a type B and type C were defined. The three manikins may now be used to draw up requirements for the provision of adequate spatial accommodations for flying personnel. For example, a seat adjustment which will support type B (short) so that he will have adequate vision for taxiing,

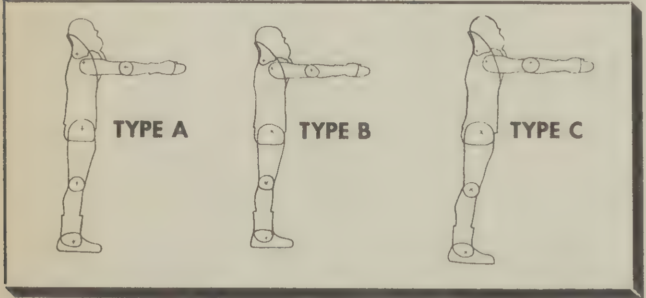

Figure 78.—Small (type B), average (type A), and large (type C) size manikins, 1/30 scale.

Figure 79.—Method of determining a flyer's center of gravity. The chair is balanced on each of two separate fulcra. The point of intersection of the two (white) lines of balance represents the center of gravity. The photograph is a composite of the two positions of balance.

and also maintain type C (tall) in such a manner that he will not have to slump to his gun sight or to clear the canopy, would be regarded as adequate for 95 percent of all personnel who will have to fly the aircraft. Another example of the application of anthropometric data is found in the design of a new seat back for troop-carrying aircraft which was based on dimensions of troops, proper location of supporting members, and provision for the assumption of postures minimizing motion sickness.

With regard to escape hatches and the problem of emergency escape from aircraft, two factors are of particular importance. First is the need for adequate training of personnel in methods by which they best may escape through hatches. Full consideration should be given to training methods which allow crew members to practice emergency escape by actual use of the hatches against the time when it becomes necessary to use them with only seconds to spare. Second, there are dimensional requirements for escape hatches which should be met. For example, a top ditching hatch should not be less than 18 inches in diameter or 18 inches square. Requirements for other hatches have been established.

In the light of the increased performance of aircraft it has become more important that the body of the flyer

be maintained as close as possible to the center of gravity of the aircraft. From an engineering standpoint, the actual center of gravity of the flyer seated in the required position must be established. This can be done by a relatively simple method, as shown in figure 79. The subject is seated in a chair supported on a tripod arrangement. The chair is then balanced first on one and then on the other of two separate fulcra. The intersection of the two vertical lines of balance represents the center of gravity.

Relation of Body Measurements to Personal Equipment

Because of the immediate and urgent nature of wartime research, personal equipment has received more attention than other applications of AAF anthropometric study. In personal equipment, the relation of man to material is immediate and obvious. Construction of full-scale models and studies in the relationship of body size to aircraft design are relatively long-term projects; they are of necessity secondary to those undertaken in response to an urgent request from a combat theater for a large number of some experimental item of personal equipment for which dimensions and proportions of each size must be worked out immediately.

To present requirements in personal equipment based upon variations in the dimensions of relevant portions of the anatomy, anthropometic surveys similar to those previously mentioned were undertaken. In addition to the measurements of total body proportions in 3,000 aviation cadets and 800 gunners, about 2,000 subjects, all flying personnel, have been measured for dimensions applying solely to the head and face. Additional data have been collected from approximately 1,400 flying crew members in order to establish clothing size requirements. Numerous other smaller surveys have been undertaken to investigate and solve specific problems.

STATURE & CHEST TOTAL ISSUE
RATIO 1 FIGHTER PILOT: 9.2 TOTAL BOMBARDMENT—PERCENTAGES

CHEST

STATURE	32	33	34	35	36	37	38	39	40	41	42	43	44	
60														
.5				0.09		0.08								0.17
61					0.09									0.09
.5														
62		0.09	0.14	0.09	0.17									0.49
.5	0.08	0.09			0.09									0.26
63	0.09			0.08	0.17	0.08	0.11		0.08					0.61
.5	0.08				0 03					0.08				0.19
64		0.17	0.26	0.15	0.12	0.23	0.26		0.08					1.27
.5		0.06	0.11	0.82	0.03	0.60		0.09						1.73
65		0.09	0.06	0.18	0.38	0.93	0.20	0.15	0.08					2.07
.5			0.47	0.60	0.72	1.20	0.55	0.12		0.08				3.74
66			0.52	0.56	0.77	0.71	0.26	0.09	0.06					2.97
.5		0.06	0.06	1.08	1.00	1.09	0.67	0.20	0.24					4.40
67			0.09	0.88	1.10	1.39	0.35	0.45	0.17		0.17			4.60
.5		0.15	0.89	1.37	1.80	1.66	1.57	0.58	0.87	0.18				9.17
68			0.47	0.99	1.54	1.48	1.11	0.85	0.21	0.03	0.09			6.77
.5		0.03	0.56	1.23	1.33	1.74	1.28	0.55	0.08	0.35		0.08		7.25
69		0.20	0.26	0.58	1.21	1.69	0.99	0.35	0.30	0.17	0.85			6.60
.5		0.36	0.66	1.40	3.49	3.01	1.80	2.03	0.87	0.56				14.20
70	0.08		0.70	0.66	1.25	1.53	0.81	0.58	0.21	0.29	0.09			6.18
.5			0.26	0.46	1.41	1.62	1.22	0.75	0.38	0.20	0.17			6.47
71		0.03	0.09	0.78	0.65	1.44	0.95	1.29	0.29	0.12	0.26			5.90
.5				0.26	0.92	1.81	1.82	1.14	0.68	0.32		0.09	0.32	7.36
72			0.03	0.09	0.36	0.65	0.42	0.09	0.12	0.09		0.09		1.94
.5				0.08	0.21	0.44	0.60	0.55	0.12	0.08	0.12			2.20
73			0.27	0.44	0.36	0.47	0.58	0.09	0.26	0.18				2.65
.5					0.09	0.08	0.18		0.09	0.09	0.09			0.62
74							0.08	0.18	0.09	0.27				0.62
.5					0.12	0.18	0.09	0.09						0.48
75							0.09			0.03				0.12
.5					0.09			0.09						0.18
76														
.5							0.09							0.09
	0.33	1.37	5.90	12.87	19.60	24.11	16.08	10.31	5.28	3.12	1.84	0.28	0.32	101.29

Figure 80.—Typical master chart for basic requirements in clothing.

Figure 81.—Standard models for size tests of flying helmets.

It is evident that the design and construction of personal equipment must be considered from the standpoint of physical dimensions as well as from that of physiological requirements. The complexity of the equipment which must be worn makes the complete integration of individual items essential for maximum efficiency. Anthropometric data have been translated into tailors' measurements to establish basic requirements. Jackets, trousers, helmets, and gloves have been sized and charts (figure 80) prepared which are utilized routinely in the design, sizing, procurement, and issue of clothing for AAF flyers. Master charts demonstrate the adequacy of any one type of clothing and the percentage distribution of sizes which must be procured. Thus, the number of sizes required and the dimensions for each size will be tentatively established for a proposed garment, based on knowledge of its function, design, material, and associated clothing. A sample of each size is made and tested on subjects of known dimensions, and the size schedule modified as indicated. These dimensions are included in the specification. Finally, the percentage of each size in the total production is determined.

Samples of flying helmets are routinely submitted for size tests before full production begins. These tests are carried out with the aid of standard size models (figure 81). A study of glove sizing has led to the construction of a glove size tester.

With the standardized integration of flying clothing, helmets, and masks, it becomes a relatively simple matter to establish the size requirements which must be met by flak suits and flak helmets. Since goggles are an integral part of the head equipment, similar principles of determining size requirements apply to them.

The study of oxygen masks presented an important and often intriguing problem. It was the first attempt to apply anthropometry to aviation medicine and its emphasis, at first on analysis and evaluation, soon shifted to original design. Even before head models were employed, all available masks were thoroughly tested for fit on series of individuals measured according to a facial survey. Successes and failures of each size of mask were related to facial dimensions, and proportions of AAF flyers fitted could then be estimated. Recommendations were made for redesigning and resizing, and specific data supplied, with the result that subsequent masks have a much higher percentage of fits.

It has been determined that three sizes are required in AAF masks, and the percentages of these sizes have been established for general production and for issue to specific groups of flyers. It has been found, for example, that fighter pilots and, especially, photographic reconnaissance pilots require a larger proportion of small and medium sizes than do members of bomber crews.

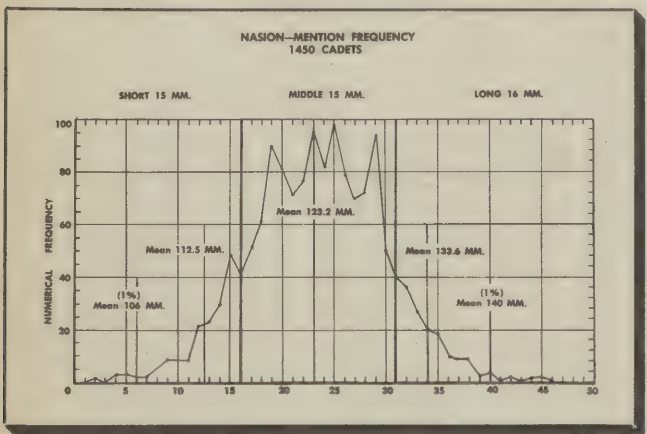

Figure 82.—Distribution curve of nasion-menton dimension in aviation cadets.

Figure 83.—Laryngeal mask. Utilized for supplying oxygen to patients who have undergone tracheotomy.

The basic dimension determining the size requirements of an oxygen mask is the nasion-menton, obtained by measuring the distance from the root of the nose to the base of the chin. Figure 82 shows the distribution curve of this dimension in 1,450 aviation cadets. Table 11 offers a more detailed breakdown of distribution, covering the various requirements for different groups of flying personnel.

In addition to the routine applications of the knowledge gained from a systematic study of the sizes of flying personnel, it becomes necessary on occasion to apply this information to new designs of equipment meant for more specific use. Figure 83 illustrates an unusual application of such data in the design of a laryngeal mask. The A-13 pressure-demand mask was also designed on the basis of these dimensions.

TABLE 11

DISTRIBUTION OF NASION-MENTON MEASUREMENTS FOR OXYGEN MASK SIZES

Nasion-Menton	*Aviation Cadets*	*Fighter and Photo-Recon Pilots*	*Commissioned Bombardment Aircrew*	*Enlisted Bombardment Aircrew*	*Total Bombardment Aircrew*	*Total Issue*	*WASP*	*Flying Nurses*	*ROTC Negroes*
96 to 115 mm (small mask)	11.02	13.71	10.07	10.85	10.52	10.83	50.62	71.82	5.30
116 to 130 (medium mask)	76.92	81.23	76.60	76.59	76.59	76.96	48.69	28.18	71.97
131 to 152 (large mask)	12.06	5.06	13.33	12.66	12.99	12.21	0.69	0.00	22.73

CHAPTER XIII

AIR EVACUATION OF THE SICK AND WOUNDED

In the AAF, the transportation of patients by airplane is assuming greater importance daily. An estimated total of over 700,000 sick and wounded patients of the American and Allied forces were carried from the beginning of the 1942 counteroffensive in the South and Southwest Pacific to the end of 1944. More than 75 percent of this total was transported in 1944, with the Ninth and Twelfth Air Forces handling the larger part of the increased traffic as a result of the offensive in Western Europe. Despite the large number of critically wounded cases, the death rate in flight has been extremely low, only 7 per 100,000 patient trips.

Airplanes are not available for assignment as ambulances, and, by necessity, aerial evacuation is accomplished by cargo aircraft, the C-47, C-46, C-54, and C-64 types, which are equipped so that litters can be loaded within a few minutes after cargo is removed. *(See figure 84.)* In present-day warfare, it is necessary to consider the evacuation of casualties in terms of time rather than in terms of distance.

ADVANTAGES.—Air evacuation possesses several distinct advantages:

1. *Speed.* It provides unusual speed and short duration of the evacuation process from any zone: from the

Figure 84.—The webbing strap type litter support installation in a C-47 airplane with litters in place. There are 6 tiers and a capacity of 24 patients.

battlefield, from fixed installations of such areas as the Caribbean and Northwest Command, or from the scene of an accident to an air field nearest a hospital where treatment may be given.

2. *Comfort.* Instead of a rough and long ride in a motor or train ambulance, comfort is assured.

3. *Safety.* Maximum safety is provided.

4. *Economy.* The economy of medical personnel and field equipment is obvious.

5. *Care.* Patients receive constant observation and care during flight by trained medical enlisted men, flight nurses, or flight surgeons.

6. *Earlier Treatment.* Early institution of definite treatment often may make the difference between life and death, or between the saving and losing of an extremity. More adequate as well as early treatment for badly injured and seriously ill patients is obtained through air evacuation, because they can be transported rapidly. This is especially important if the patient requires major surgical attention. Patients who have burns of the face and hands, injuries to the eyes, wounds of the joints, gunshot fractures, or wounds of the lungs are particularly benefited by airplane evacuation to surgical centers where the best personnel in diagnostic and therapeutic procedures are available.

7. *Reduced Land Traffic.* Congestion on land lines of transportation is reduced.

8. *Heightened Morale.* The morale of wounded soldiers is much improved when they know that such service is available.

DISADVANTAGES.—Airplane ambulances have some disadvantages:

1. *Fields and Service.* Reasonably good landing fields and servicing facilities always are required.

2. *Weather Limitations.* Usefulness is lost or reduced during adverse weather.

3. *Care of Patients in Airplanes.* As explained in Chapter II, anoxia normally causes an appreciable handicap at altitudes in excess of 10,000 feet. Any clinical condition such as pneumonia or damage to the lungs caused by gas can be tolerated less well at high altitudes than at sea level; however, anoxia usually can be controlled by the administration of oxygen. Air evacuation generally involves altitudes well below 10,000 feet. Patients requiring supplementary oxygen at these altitudes would also need it at ground level. Injuries to the head cause a depression of the oxygen saturation of the arterial blood, and any such patient may require oxygen at ground level. In this group are included patients who have lost much blood as the result of wounds, patients who are in a state of severe shock, or those who have severe and sudden infections. Patients who have severe heart disease or severe symptoms of poisoning by the sulfonamide group of drugs should receive unusually careful attention during flight and should be given oxygen continuously.

The hazard of aerial transportation to patients with pneumothorax is present because the volume of air (saturated with water vapor at 37°C, or 98.6°F) in a pneumothorax increases with altitude according to Boyle's law, as illustrated in the roentgenograms in figures 85a and b. For this reason, the airplane ambulance kit contains a syringe and needle for the removal of such excess chest air. The gas normally present in the gastro-intestinal tract also expands with altitude (figure 33). This results in expansion of the stomach and intestines, with possible tearing of recently sutured tissue or the forcing of gas through any openings in the intestines and the escape of fecal material into the peritoneal cavity. Patients who have intestinal obstructions, perforating wounds of the intestine, strangulated hernias, or perforating ulcers of the stomach should be transported only when it is possible to fly at very low altitudes. When evacuation of this type of patient is necessary, the stomach tube carried in the airplane ambulance kit should be inserted through the nose or mouth into the patient's stomach so that any excess amount of gas will be expelled. If possible, the patient also should be given an enema before take-off and a rectal tube should be insert-

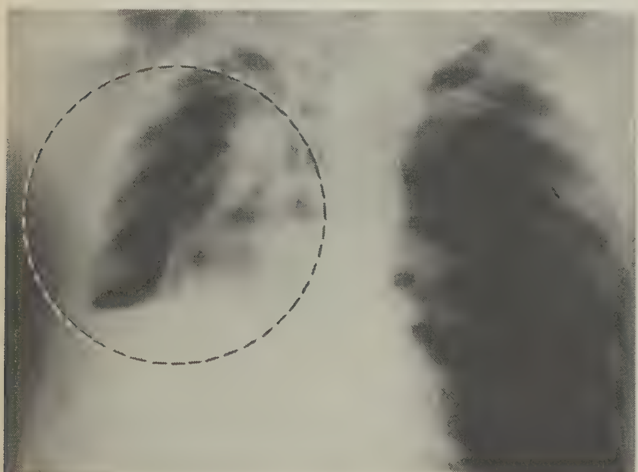

Figure 85a.—Pneumothorax at ground level.

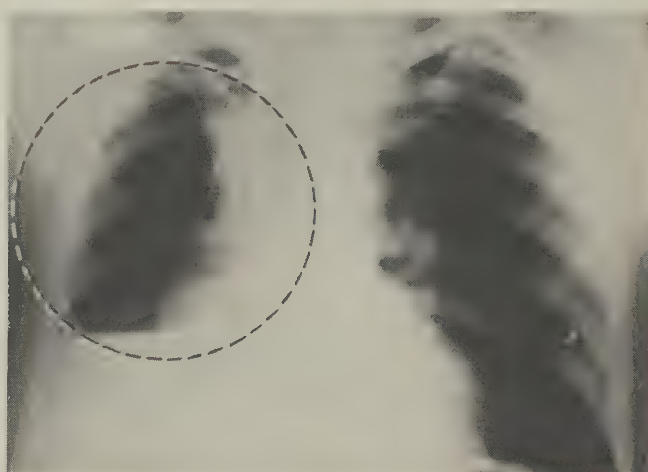

Figure 85b.—Pneumothorax at an altitude of 10,000 feet.

ed at fairly frequent intervals if an altitude in excess of 2,000 to 3,000 feet is attained.

Provision is made in the airplane litter installations so that the majority of the litters can be tilted at an angle of 15 or 20 degrees. This provision is of value, since it is well known that patients who have injuries of the head, neck, and chest should be transported in the head-up position, whereas patients in a state of shock should be transported in the head-down position. All patients should be retained in place on the litters by litter straps (figure 84).

Airsickness has not been a problem in air evacuation, its incidence among litter patients being extremely low.

Air evacuation within theaters of operations is carried out by Medical Air Evacuation Squadrons in the Troop Carrier Command and by the Air Transport Command along all its global routes. The planes are staffed by flight nurses and medical technicians who are members of Medical Air Evacuation Squadrons and who work in a highly coordinated system directed by flight surgeons at each air base. Medical Air Evacuation Squadrons are trained in the Air Evacuation Section, AAF School of Aviation Medicine, Randolph Field, Texas.

The Aero Medical Laboratory works in close cooperation with other laboratories of the Engineering Division, Air Technical Service Command, to provide improved litter installations for all types of aircraft. Detailed information on the litter equipment of various types of aircraft has been published in a series of articles in *The Air Surgeon's Bulletin* during 1944. Details on litter installations in other aircraft may be found in subsequent issues of *The Bulletin*. In addition, a series (00-75) of Technical Orders is available, describing procedures for handling patients in the various airplanes. Answers to specific problems can be obtained from the Aero Medical Laboratory.

APPENDIX

METRIC EQUIVALENTS
(Bureau of Standards)

LENGTH

cm = .3937 in.	In. = 2.54 cm
Meter = 3.28 ft	Ft = .3048 meter
Meter = 1.094 yd	Yd = .9144 meter
Kilom = .621 mile	Mile = 1.61 Kilom

AREA

Sq cm = 0.1550 sq in.	Sq in. = 6.45 sq cm
Sq m = 10.76 sq yd	Sq ft = .0929 sq m
Sq m = 1.196 sq yd	Sq yd = .836 sq m
Hectare = 2.47 acres	Acre = 0.405 hectare
Sq Kilom = .386 sq mile	Sq mile = 2.59 sq kilom

VOLUME

Cu cm = .061 cu in.	Cu in. = 16.38 cu cm
Cu m = 35.315 cu ft	Cu ft = .028 cu m
Cu m = 1.308 cu yd	Cu yd = .7645 cu m

CAPACITY

Liter = .0353 cu ft	Cu ft = 28.32 liters
Liter = .2642 gal. (U. S.)	Gal. = 3.785 liters
Liter = 61.023 cu in.	Cu in. = .0164 liters

Liter = 2.202 lb of fresh water at 62° F

WEIGHT

Gram = 15.432 grains	Oz = 28.35 gram
Gram = .0353 oz	Lb = .454 kg
Kg = 2.2046 lbs	Ton (sht) = 907.18 kg
Kg = .0011 ton (sht)	Ton (sht) = .907 met. ton
Met. ton = 1.1025 ton (sht)	Ton (sht) = 2000 lbs

Grain = .0648 gram

PRESSURE

1 kg per sq cm = 14.2233 lb per sq in.
1 lb per sq in. = .070307 kg per sq cm
1 kg per sq m = .20482 lb per sq ft
1 lb per sq ft = 4.8824 kg per sq m
1 kg per sq cm = 0.98784 standard atmosphere
1 standard atmosphere = 1.033228 kg per sq cm
1 metric atmosphere = 1 kg per sq cm
1 standard atmosphere = 14.6959 lb per sq in.

TEMPERATURE EQUIVALENTS

To change Centigrade to Fahrenheit—$F = 9/5C + 32$
To change Fahrenheit to Centigrade—$C = (F-32)\ 5/9$

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1. AAF Memorandum 25-5: Vision at night, 14 July 1942.

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